AUBURN

UNIVERSITY

SAMUEL GINN

COLLEGE OF ENGINEERING

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Lunabotics Mining Competition Systems Engineering Paper

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ABSTRACT

A fast growing approach in determining the best design concept for a problem is to hold a competition in which the rules are based on requirements similar to the actual problem. By going public with such competitions, sponsoring entities receive some of the most innovative engineering solutions in a fraction of the time and cost it would have taken to develop such concepts internally. Space exploration is a large benefactor of such design competitions as seen by the results of X-Prize Foundation and NASA lunar excavation competitions [1].

The results of NASA's past lunar excavator challenges has led to the need for an effective means of collecting lunar regolith in the absence of human beings. The 2010 Exploration Systems Mission Directorate (ESMD) Lunar Excavation Challenge was created "to engage and retain students in science, technology, engineering, and mathematics, or STEM, in a competitive environment that may result in innovative ideas and solutions, which could be applied to actual lunar excavation for NASA." [2]. The ESMD Challenge calls for "teams to use telerobotics or autonomous operations to excavate at least 10kg of lunar regolith simulant in a 15 minute time limit" [2].

The Systems Engineering approach was used in accordance with Auburn University's mechanical engineering senior design course (MECH 4240-50) to develop a telerobotic lunar excavator, seen in Fig. 1, that fulfilled requirements imposed by the NASA ESMD Competition Rules. The goal of the senior design project was to have a validated lunar excavator that would be used in the NASA ESMD lunar excavation challenge.

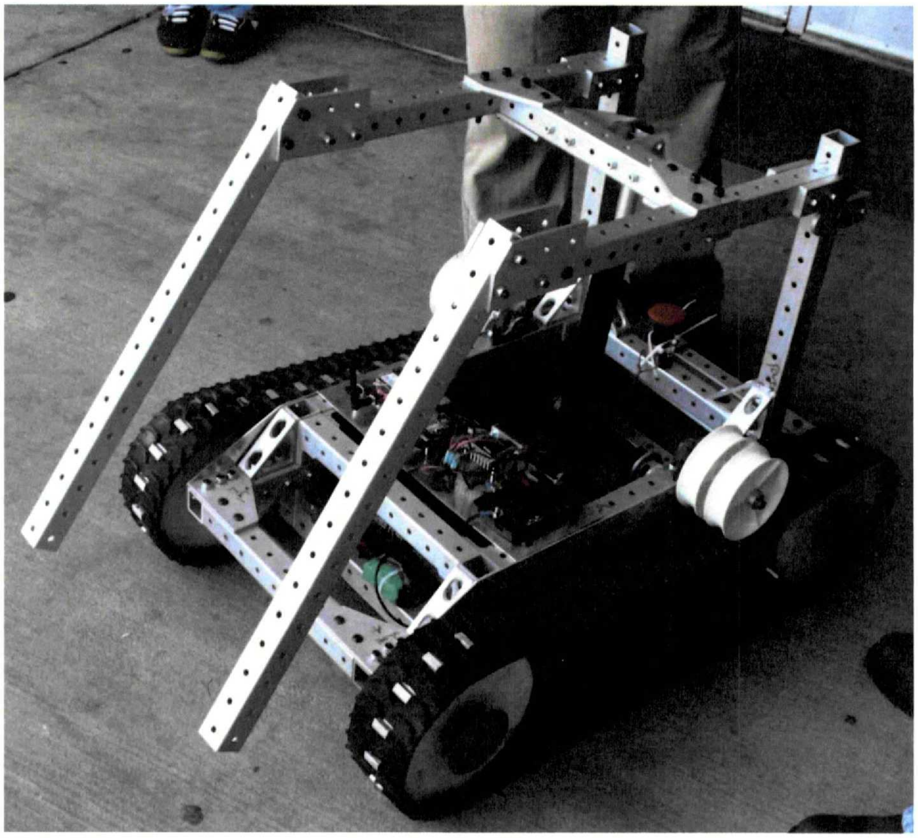

Figure 1: Excavator to date

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INTRODUCTION

The systems engineering design process involves following the Vee Chart, seen in Fig. 2, and applying the 11 system engineering steps, seen in Fig. 3, throughout the Engineering Design Process.

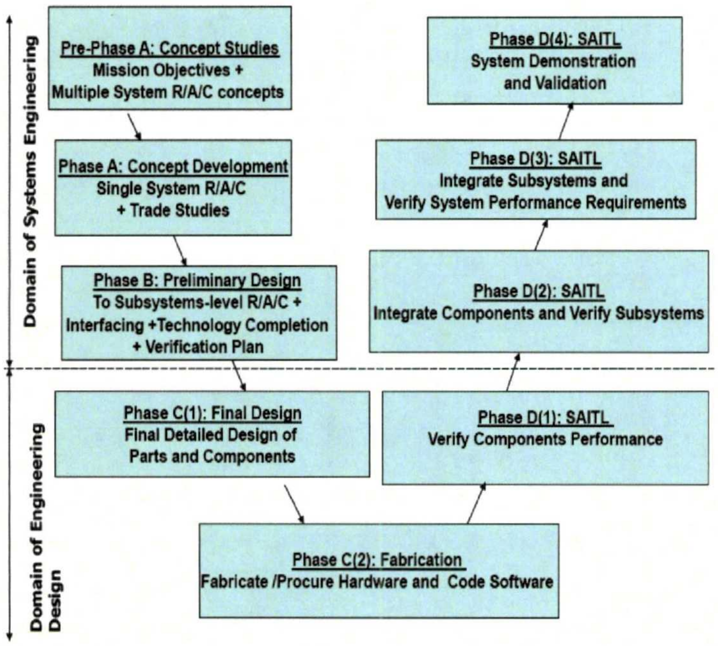

Figure 2: Systems Engineering Vee Chart [3]

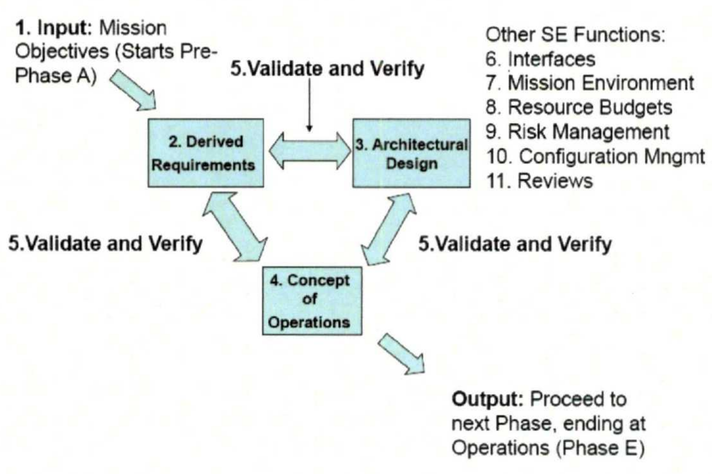

Figure 3: 11 Systems Engineering Functions [3]

The senior design course at Auburn University consists of splitting the systems engineering process into two consecutive semesters [4]. Pre-Phase A through Phase B of the Vee Chart typically occur in the first semester of senior design, and Phases C through D of the Vee Chart occur during the second semester of senior design [4].

The ESMD Challenge has been an ongoing project at Auburn University. Team Pumpernickel came onboard the ESMD Challenge project after Pre-Phase A through B had been completed. The previous group had designed and fabricated a prototype excavator for investigation of technology issues.

The prototype excavator underwent testing on Engineering Day at Auburn University, but would not be able to meet competition requirements by 24 May 2010. Team Pumpernickel decided the system requirements would best be met after redesign of the critical excavator subsystems. The overall Architectural Design and Concept of Operations remained the same in an effort to save time. The excavator is not complete at this time, but several critical subsystems have begun the verification process and will be discussed in further detail in the respective subsystem section.

It is the goal of this paper to show the usage of systems engineering throughout the design and fabrication process of Team Pumpernickel's lunar excavator for the 2010 ESMD Lunabotics Mining Competition.

SYSTEMS ENGINEERING

Mission Objective:

The mission of Team Pumpernickel is to compete in the 2010 NASA ESMD Lunabotics Mining Competition.

Mission Environment

The environment for the excavator is theoretically the surface of the moon, however for competition purposes the environment will be a simulated lunar surface in a controlled climate on site at the Kennedy Space Station in Orlando, FL.

System Requirements

The fundamental system requirements were provided by NASA in the form of official field, game play, and technical rules for the ESMD mining competition, seen in Appendix A. Other system requirements were derived in addition to the ones

provided by NASA based on Functional, Performance, Interface, Verification, and Supplementary requirements of the system. A list of the most important derived system requirements can be seen in Table 1.

Table 1: System Requirements

F	The excavator shall collect, transport, lift, and deposit the lunar simulant
F	The excavator shall be operated via telecommunications
P	The excavator shall collect at least 10kg of simulant in 15 minutes
P	The excavator shall lift the simulant at least one meter above the surface of the playing field
I	The communication system shall interface with NASA's wireless network
V	The prototype excavator shall be tested according to the functional requirements on or before 26 February 2010
V	The final design of the system shall be verified according to the Competition Rule Book requirements on or before 01 May 2010
S	The excavation hardware must be equipped with an emergency stop
S	The excavation hardware must be able to operate under semi-lunar like conditions as described by Rule 25 of the Competition Rule Book [2]
S	The excavation system shall be designed, fabricated, and verified using less than $5000.00

The requirements for each subsystem and subsequent component were derived from the system requirements and will be discussed in further detail in each subsystem's appropriate section.

Concepts of Operations

The system was initially divided into two fields: Mechanical and Electrical, and the system Con-Ops were developed based on the system requirements. The mechanical Con-Ops were derived based primarily on the functional requirements in Table 1 and can be seen in Fig. 4.

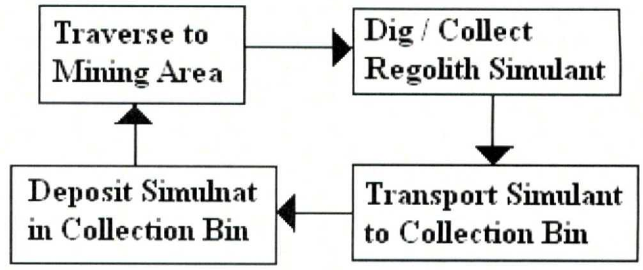

Figure 4: Mechanical Con-Ops

The resulting mechanical Con-Ops were Traverse and Dig / Transport / Deposit. The Electrical Con-Ops were derived based primarily on functional and performance requirements in Table 1 and can be seen in Fig. 5.

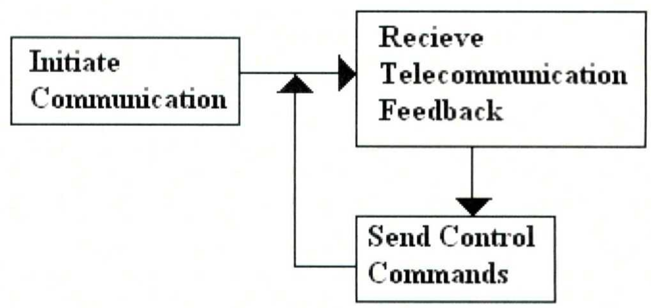

Figure 5: Electrical Con-Ops

The resulting Con-Op was Telerobotic Operation. A fourth Con-Op, Subsystems Integration was created in order facilitate the interfacing of subsystems.

Major Reviews:

Team Pumpernickel came onboard the ESMD project after the Mission Concept Review (MCR) and the Mission Design Review (MDR) had already taken place on the prototype excavator system. Team Pumpernickel conducted a Preliminary Design Review (PDR) after prototype testing on Engineering Day, this can be found in Appendix B. The PDR addressed problems pertaining to the prototype excavator and how system requirements would be met. The PDR resulted in a key decision point which involved the redesign of the critical excavator subsystems. This was decided after cost/benefit analysis was performed on the proposed prototype modifications. The Critical Design Review is scheduled to take place on 1 May 2010

and the Readiness Review is scheduled to take place on 15 May 2010. The Critical Design Review will address remaining design proposals, and the Readiness Review will address remaining actions required for preparation of the ESMD competition

Interfaces

Before each subsystem was designed in detail, a list of interfaces was drawn up so that each member knew how his component(s) would have to interact with others. This interaction was accounted for in the design of each subsystem and consequently each component by becoming a derived requirement. All interfaces were broken down into five categories dependent on what two components were being interfaced. The five categories where: Mechanical to Mechanical, Mechanical to Mechatronic, Mechanical to Electrical, Electrical to Mechatronic, and Electrical to Electrical. A list of all the interfaces and how each was accomplished can be seen in Appendix C.

Architectural Design and Development:

The overall architectural design of the excavator was developed using functional analysis of the Con-Ops of the excavator. The resulting architectural design included a Drive, Digger Arm, Frame, and Communication and Control subsystems. The architectural design layout can be seen in Fig 6.

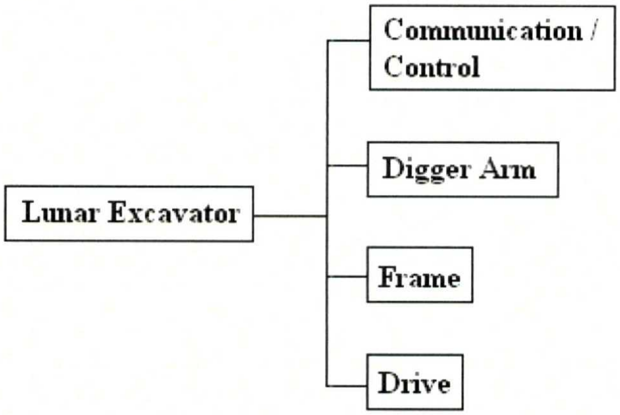

Figure 6: System Architectural Design

Frame Subsystem:

The interfacing of the three main functions led to the development of the fourth critical subsystem which allowed for ease of subsystem integration. It was decided to use a frame system to which each subsystem could be attached and interfaced. The final frame proposal resulted in a body-on-frame design composed of 8020 Inc. aluminum components and aluminum exterior body panels.

The main focus for the new design of the frame subsystem was driven by increasing rigidity of the frame subsystem. This requirement was derived after the testing of the prototype excavator and the interfacing of the other subsystems. The prototype excavator's frame was composed of thin wall carbon fiber tubes joined by G-10 Garolite. The weak nature of hollow tubes caused deformations, as seen in Fig 7, and the prototype frame subsystem did not meet rigidity requirements even after steps were taken to remedy such issues.

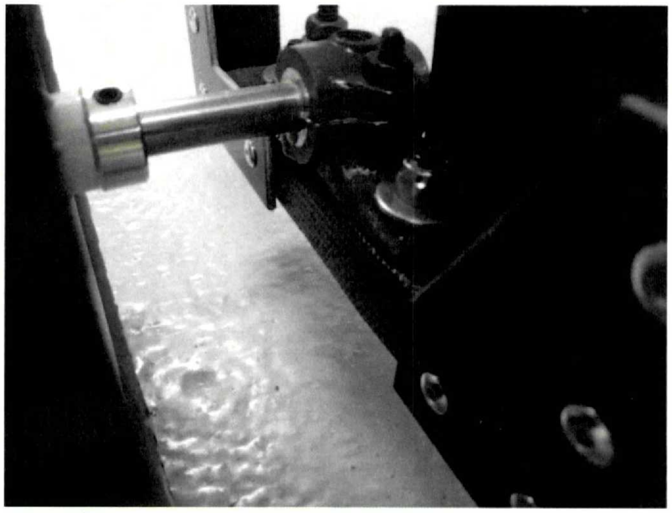

Figure 7: Bulging Carbon Fiber Tube at Drive Interface of Bearing Mount

The main focus for the new design was driven by increasing rigidity of the frame subsystem. Other driving derived requirements for the frame subsystem were:

- The frame shall not weigh more than 30kg
    - Derived from the overall weight requirement of the excavator system as per NASA Competition Rules [2]
- The frame shall not exceed 19.5”
    - Derived from the overall width requirement of the excavator system as per NASA Competition Rules [2]
- The frame subsystem shall be fabricated on or before 17 March 2010

The product hierarchy, seen in Fig 8, was developed after analyzing the requirements imposed on the frame subsystem.

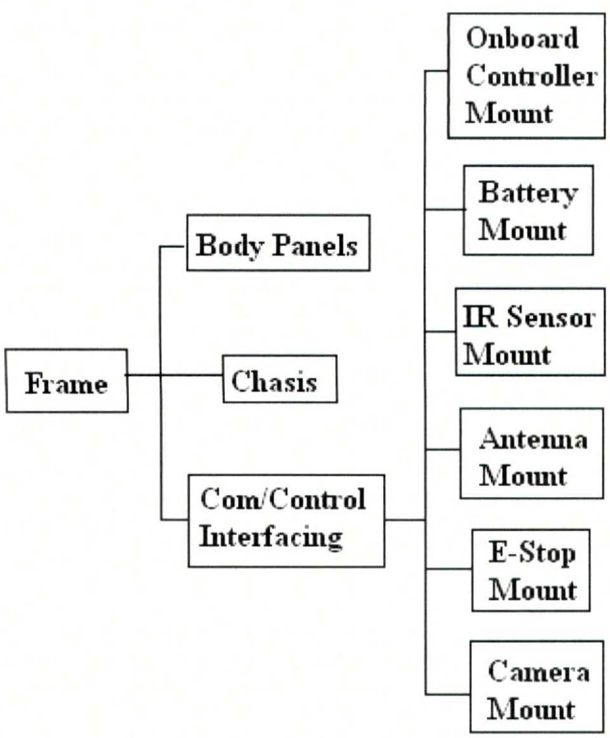

Figure 8: Frame Subsystem Product Hierarchy

Trade studies were conducted after the basic architectural design for the frame subsystem had been laid out. The most important trade study involved an investigation of Super Droid Robots, Inc. HD2 Treaded Tank Robot seen in Fig 9 [5].

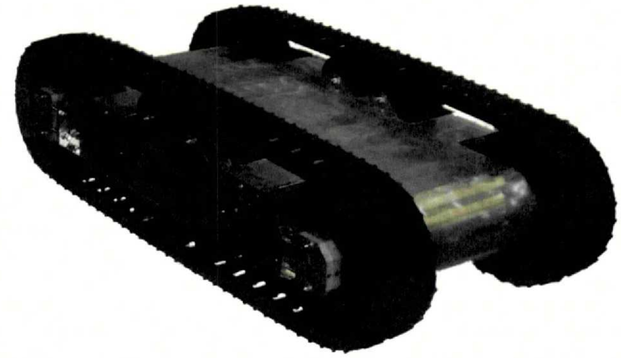

Figure 9: Super Droid Robots, Inc. HD2 Treaded Tank Robot [5]

The HD2 Robot consists of a welded aluminum frame to which the HD2 drive and control subsystems are interfaced [5]. One possibility for the design of not only the Frame but also the Drive and Com/Control subsystems of the new excavator involved purchasing the prefabricated HD2 Tank Robot. This option was deemed not feasible due to the price of the HD2 Tank. The HD2 Frame, Drive, and Com/Control subsystems would cost over $6000.00 in order to meet system requirements. This cost would not include the addition of the Digger Arm subsystem. Super Droid Robots, Inc. offers other smaller and less expensive prefabricated treaded tank robots, but these were deemed not feasible due to the inability to meet the performance requirements of the excavator system.

It was determined to design and fabricate a new frame after the trade studies were complete and after verification of the prototype excavator. The basic architectural layout was determined to mirror the prototype excavator’s layout in order to reduce the design time. The driving requirement for the new frame design involved increasing frame rigidity. The design of the frame subsystem was based on

- Developing a decision matrix for determining the material to be used
- Conducting fabrication feasibility tests for frame joining options
- Researching the underlying design motives of the selected material for interfacing of other subsystems.

The material choices for the new frame consisted of either reusing old 8020 Inc. aluminum (www.8020.net) or using new steel. The size and profile of the steel was chosen such that weight of the steel components equaled the weight of the 8020 components. It was decided to use 8020 Inc. aluminum after constructing a decision matrix. The decision matrix for the frame design can be seen in Table D.1 of Appendix D.

The method for best joining the 8020 frame components was analyzed based on fabrication feasibility tests and the original intent of design for 8020. 8020 was originally designed to be bolted together, eliminating the need for welding [6]. Welding components, however, is lighter than using fasteners as with traditional 8020. The option of welding 8020 was eliminated after the fabrication tests revealed extreme difficulty in welding.

The inherent design of 8020 was not only to eliminate welding and provide an easily fabricated base frame, but also to provide ease of attaching other components or subsystems to the base frame [6]. This was an influencing factor in choosing 8020 because it lent the easiest interfacing between the frame and the other subsystems. The Drive and Digger Arm subsystems need only take into account the available connecting options as quasi requirements.

The design of the body was based primarily on past prototype verification. The prototype verification revealed a lack of structural integrity between the interface of the Prototype Drive and the Prototype Frame subsystems. The resulting design of the body panels consisted of using aluminum sheet panels riveted to the base frame. The rivets were staggered providing greater structural strength to flat plate bending. Additional design decisions were made in an attempt to improve the Prototype Drive and Prototype Frame interface which will be further discussed in the Drive Subsystem section.

The aluminum sheet metal was determined satisfactory for serving as a base mount for the Com/Control subsystem. Proper steps need only be taken to ensure insulation for the Com/Control subsystem and to ensure wireless antenna reception. Battery mounts would be similar to the HD2 Tank, since the excavator batteries are identical to the HD2 Tank batteries. The controller and other PC boards would be mounted in the middle of the cavity in a similar fashion to the HD2 Tank, and the required kill switch would be added at a later time.

The resulting frame design consisted of a body-on-frame design fabricated out of salvaged 8020 Inc. aluminum HT slot frame parts joined using traditional fastening options (nuts and bolts) and a new aluminum sheet metal body. The resulting complete chassis can be seen in Fig. 10 and the body panels can be seen in Fig. 11.

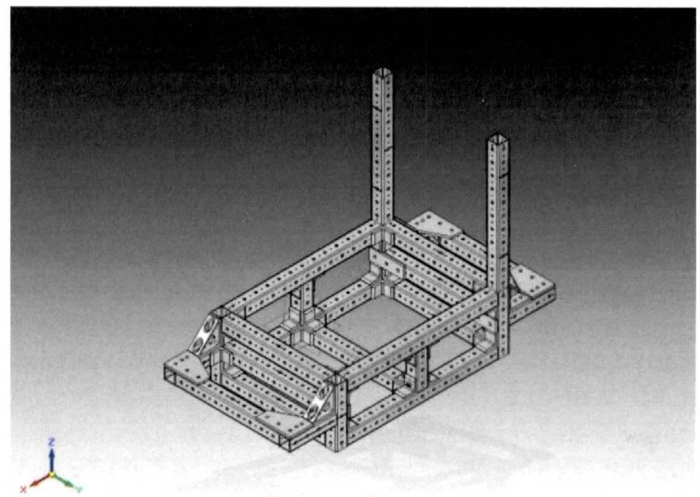

Figure 10: Body-on-Frame design for the Excavator

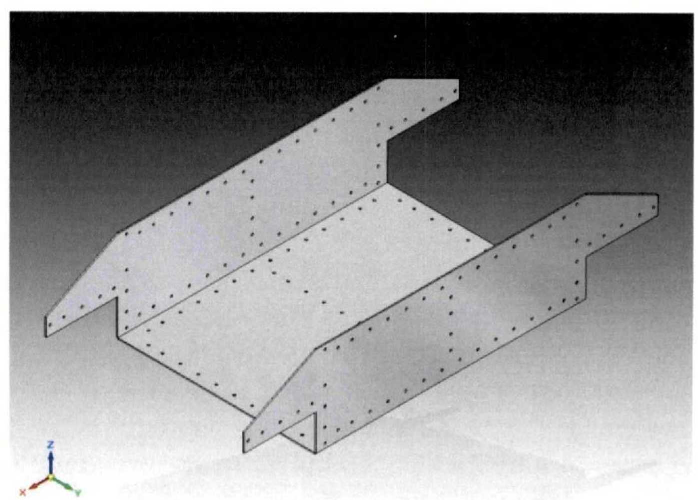

Figure 11: Body Panels for Frame Subsystem

The frame components and subsystems were verified before manufacturing based on component

mating, overall dimensions, structural integrity, and approximate weight using Solid Edge. The components were then manufactured and installed piecewise. The resulting frame subsystem can be seen in Fig 12.

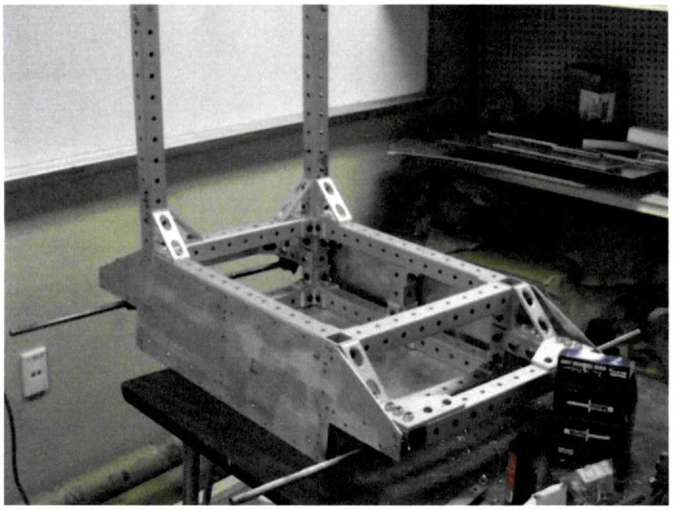

Figure 12: Assembled Frame Subsystem

The interfaces of the Frame subsystem with the Drive and Com/Control subsystems were verified, and will be discussed in the "Subsystem – Subsystem Verification" section. A bill of materials for the frame subsystem can be found in Table E.1 of Appendix E.

Drive System:

In order for the excavator to complete its tasks it must be able to move. There are many ways to do this and the drive system design will be described in detail shortly. Additionally with the excavator weighing as much as it does or can the drive system must also be robust. The outcome of the design process led us to settle on a simple track drive system. The system consists of one tread for each side, along with one motor per wheel; giving us a total of four motors. The power transmission is achieved by employing a chain and sprocket gear system. The main advantages to this system are zero degree turning radius, ability to traverse multiple terrains, and simplicity of design.

The main focus for the drive subsystem was driven by increasing the turning torque provided by the motors during zero degree turns. Other driving derived requirements for the drive subsystem were:

- The drive wheels shall not be mounted directly on the motors
- The treads shall be properly tensioned and aligned
- The wheel shafts shall be supported such that they experience minimum deflections

The product hierarchy, seen in Fig 13, was developed after analyzing the requirements imposed on the drive subsystem.

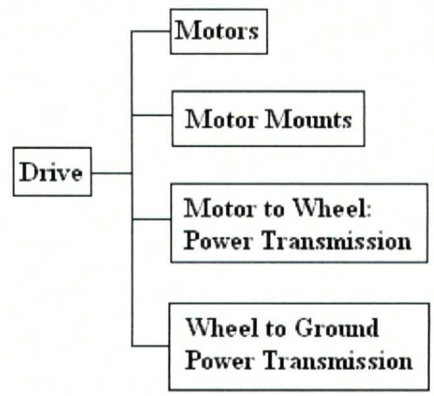

Figure 13: Drive Subsystem Product Hierarchy

Now that the frame had been designed the next step was to look into the drive system. The first thing that needed to be done was to assess the performance of the drive system that the prototype excavator used. The prototype had two motors that were directly attached to two drive wheels that drove the treads. The vehicle turned by simply having one side go forward while the other side goes in reverse, this type of steering is called skid steer. Additionally the prototype had both motors mounted directly to the side panels with no internal support. Once the system was finally installed in accordance with the previous design it was obvious that the design would not work, there was too much deflection in the system which made it impossible for the treads to remain on the wheels for any substantial amount of time. An example of such deflection is shown in Fig 14

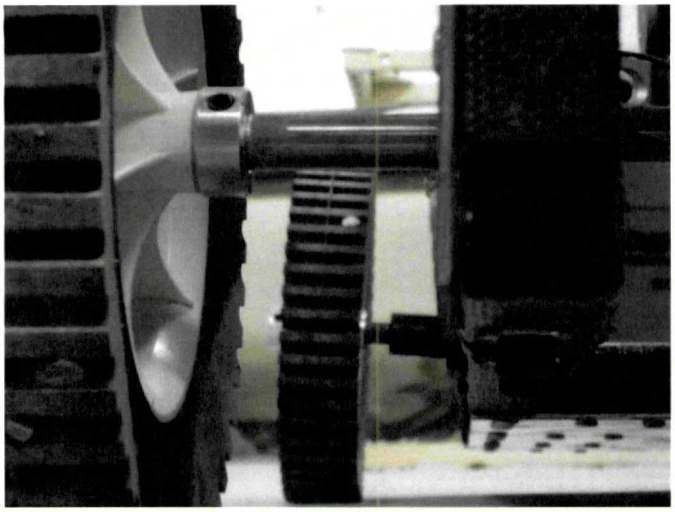
Figure 14: Shaft Deflection on Prototype

The main issues arose in the mounting of the motors, power transmission, and the mounting of the drive shafts. Solutions to all of these problems were discovered and will be discussed in the detailed design of the drive system. Engineering Day was used for verification purposes; the performance of the excavator was sub-par to say the least. Now that a base had been established for the drive system and it was noted that a new design was required the next task was brainstorming and coming up with several options; then narrowing those down to a group that are both feasible and efficient in providing the motion for the excavator. Once brainstorming was complete and the list narrowed only three options remained.

- Improving upon the treaded design that was employed on the prototype
- Changing to a traditional drive system similar to what most cars employ
- Switching to a multi-wheeled system that uses skid steer for turning

Ultimately the treaded design was chosen for reasons to be explained momentarily.

As mentioned, one choice was a traditional drive system similar to what most cars use today. What this would entail is a four wheel system with the rear two wheels being driven by independent motors and the front two wheels would be the steering wheels, and would turn just like the front wheels in a traditional automobile. The power transmission from motor to drive wheel would be accomplished by a chain and sprocket system. A major cause for concern was the design of the steering linkages, with the timeline being what it is for this project a complete design of a complex steering system would be impractical. Additionally with only four wheels a limited amount of surface area for the excavator to ride on, this could permit the excavator to sink into the regolith and render it motionless. Lastly, and maybe the most important argument against this design is cost, this design does not call for the use of many parts, if any from the prototype. Taking into account these three main concerns it was decided that this design was not a good fit for this application so it was discarded.

The other alternative discussed was a multi wheeled system that uses skid steer. This system is similar to the previous alternative in that it uses four wheels to support the weight of the excavator and two motors to provide the power; however where this system differs is in the steering. This design calls for the use of skid steer, which as discussed earlier is the use of differential velocities to turn a vehicle. The main concerns with this design were the lack of surface area, also there was large concern about turning in regolith with this system. Since it only has two motors when the excavator went to turn it was believed that it would simply dig itself into the dirt since the front wheels would essentially dig into the regolith instead of skidding over the top like desired. This system also required for all of the parts to be purchased and most of the parts from the prototype to be scrapped. Taking into account the budget and the concern over turning it was decided that this system too was unacceptable.

The next step was developing a detailed design of the drive system and components after an architectural design had been decided. Since a tread system was to be employed many of the parts from the prototype were able to be salvaged. Among those parts was a tread set that the previous group had purchased along with the wheels that were machined to match the timing of the treads. Also able to be taken were the two motors that they had purchased to drive the treads. The previous team had

purchased a set of treads from super droid robots and instead of purchasing the wheels as well they machined them in our on-campus machine shop.

Here is really where the design of the current system began, as mentioned above there were some major issues with the previous system that had to be corrected. So the initial task was to solve those issues so that the system could be tested to set a baseline for performance. There are several key solutions that are implemented in the current design to eliminate the issues that were experienced with the prototype. Among those are internal motor mounts to eliminate motor deflections, the side panel which serves as the interface between the drive and frame systems, being made out of aluminum in order to reduce deflections, and also the addition of a chain and sprocket power transmission system. The chain and sprocket is by far the most crucial addition, the old design would not produce enough torque for the excavator to turn on any surface, and the motors that were installed were decided upon by looking at how fast they could propel the excavator so it had great speed in forward and reverse. So in order to increase the torque a 10 tooth drive gear, 30 tooth sprocket, and 10 feet of #35 ANSI chain were purchased and installed in the system as shown in Fig 15 & 16.

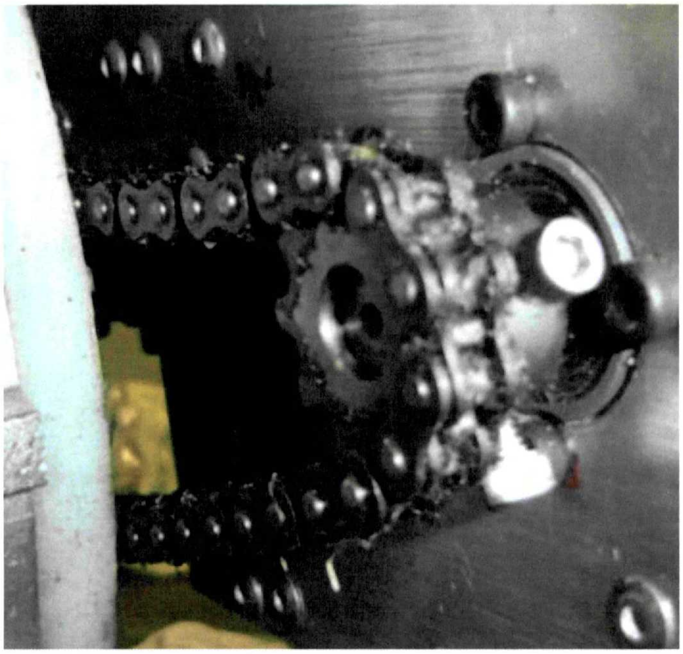

Figure 15: Installed Drive Sprocket with Chain

Figure 16: Installed Wheel Sprocket with Chain

This not only produced a 3:1 reduction in the drive system but also allowed for the motors to not be directly mounted to the drive wheels, which was a key goal of the design. Now that the drive wheels were no longer mounted directly to the motors the issue of shaft deflections could be easily addressed, the solution that was chosen was to use solid shafts that would run the width of the excavator, both the driven wheels and the un-driven wheels would ride on these shafts and spin freely. The last of the major issues with the previous design was the tension of the treads; the supplier was contacted and provided the information on the amount of tension the treads should be under. Next a tensioning system was to be designed that would keep a constant tension in the system. The result was an idler pulley attached to a rotational spring that would allow for flexibility in the treads while still keeping them in constant tension. This design can be seen in Fig 17. So through these design alterations and additions all of the initial concerns with the design were resolved.

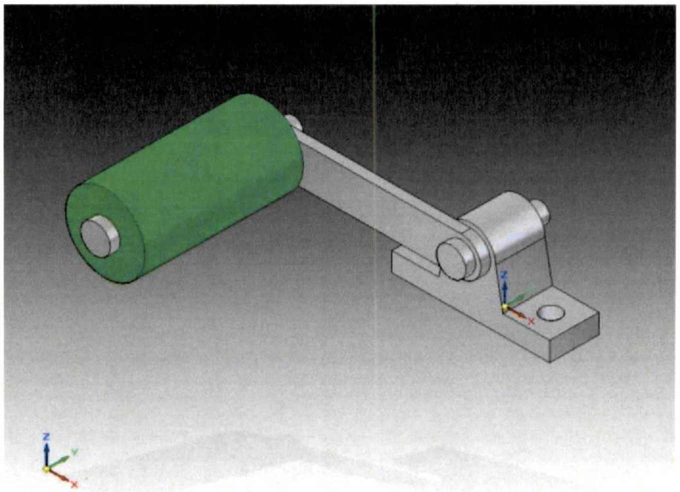

Figure 17: Design of Tensioning Device

Once the system was installed it was taken for a test run and performed admirably on most surfaces, however the excavator still experienced some difficultly turning in rougher terrain. In order to address this, the design was revisited and several trade studies were performed. The ultimate decision made was to purchase two additional motors resulting in the excavator having all four wheels driven. This would provide more than adequate turning torque in all surfaces. Since part of the design of the frame was for it to be "open" there was plenty of room for this addition. A full bill of material for the drive system can be found in Table E.2 of Appendix E.

Unfortunately, since the drive system has not been entirely installed the verification of it has yet to be fully preformed. However through previous tests and trade studies this design is thought to be sufficient for any terrain that the excavator could experience, on this planet or any other.

Digger Arm:

The design of the Digger Arm subsystem was driven by the following derived requirements:

- The Digger Arm shall lift the simulant at least 1m
- The Digger Arm shall collect at least 10 kg
- The Digger Arm shall be fabricated with salvaged parts

The product hierarchy, seen in Fig 18, was developed after analyzing the requirements imposed on the Digger Arm subsystem.

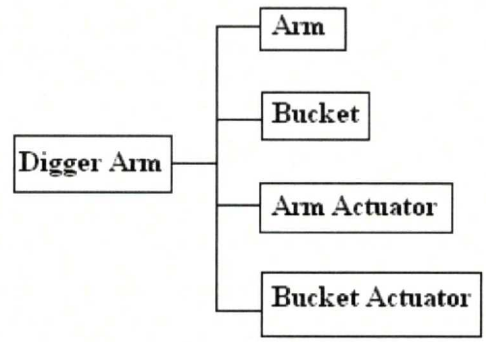

Figure 18: Digger Arm Product Hierarchy

The Digger Arm subsystem was separated into two components, the Arm Boom and Bucket components.

Arm Boom:

The design of the Arm/Boom subsystem was driven by the following derived requirements:

- The pivot point of the bucket subsystem shall lift higher than 1.15m
- The Arm/Boom actuator shall not exceed 1300 lbs dynamic load

There were many concepts of the digger arm which were sorted through for a possible design. The forklift, overhead scoop and dump, front end loader, and back hoe were all designs which were under consideration as a possible design to use on the excavator. The Forklift is front heavy and consisted of many parts. The overhead scoop and dump required a greater field of vision and is likely to miss the dumping bin. In order to operate the back hoe, the excavator had to be very heavy; it required more actuators, and a smaller bucket. Considering the alternatives, the team decided to use a front end loader.

We designed the front end loader to be simple and effective. After the design of the first concept, it was noticed that speed was a huge problem. This problem was caused mainly because of the height where the bucket arm is pivoted in accordance to where it is pivoted on the bucket, see Fig 19.

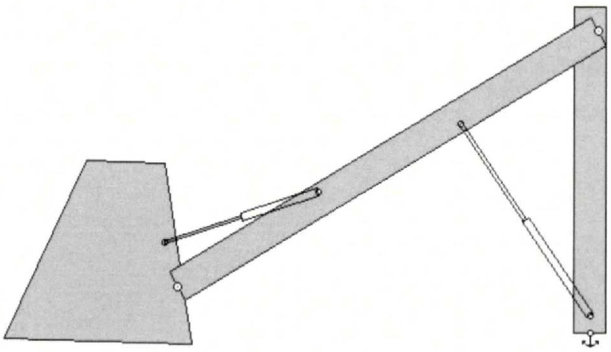

Figure 19: Prototype Arm Design

To have a design which could handle the moment caused by an instant stop of the excavator while it is traveling at full speed and also rise faster than the conceptual design, the height of the arm's pivot position must be reduced, see Fig 20.

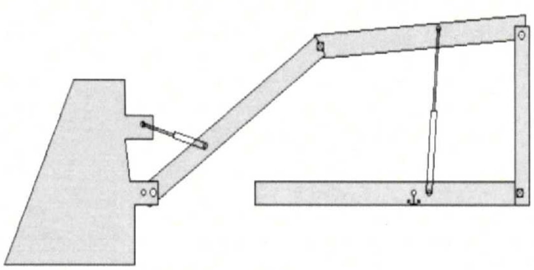

Figure 20: Proposed Arm Design

Reducing the height of the pivot position caused other problems which had to be solved. One problem was not being able to reach the dumping bin. Because of the reduced height of the pivot position, when lifting the arm we needed a longer length to reach the dumping bin. This was a simple solution but the longer length causes us to have to use a shorter bucket because of the length restrictions in the rules of the competition. If we position the shorter actuator accordingly, we are able to make the rise time three times faster, load size heavier, and also maintain a stop of the excavator when traveling at full speed. The actuator which we currently have is offered with a shorter stroke length but unfortunately, it is on backorder and will not be available before the subsystem design deadline. Figure 21 shows the assembly of the arm on the frame and the shorter actuator.

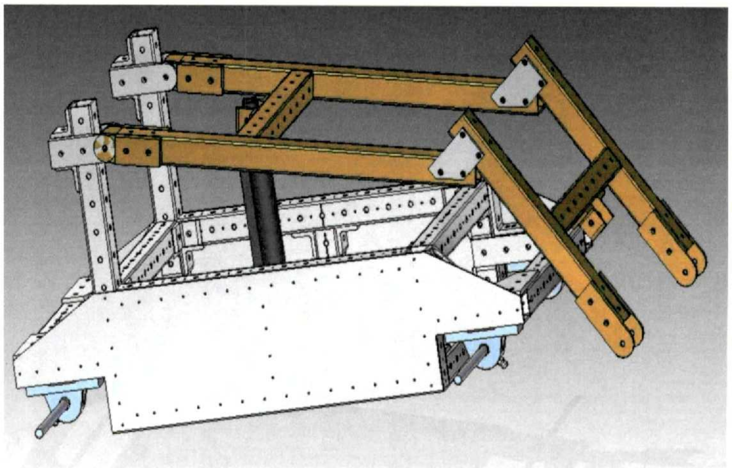

Figure 21: Proposed Arm Interfacing

For competition deadlines, we were able to come up with a design which could use our current actuator while the shorter actuator is being ordered. To do this we increased the height of the pivot which is used to connect the actuator to the arm. A Bill of Materials may be found in Table E.3 of Appendix E.

Bucket:

The bucket system's derived requirements stem from the requirements imposed upon the Digger Arm subsystem and the Prototype Excavator Bucket subsystem. The prototype bucket design consisted of a Garolite G-10 bucket that was attached to the main arm via a steel shaft as seen in Fig 22.

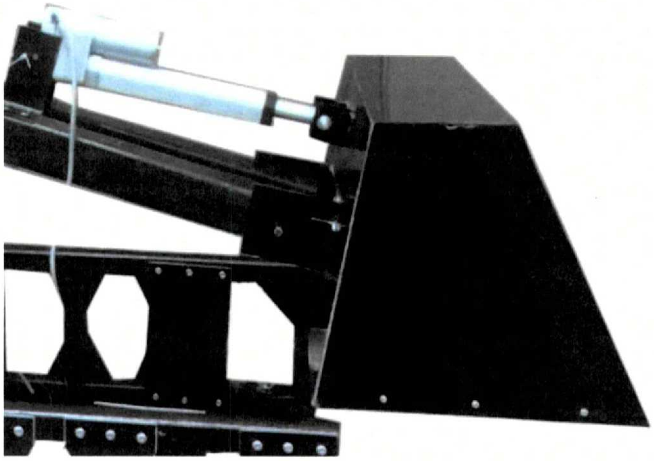

Figure 22: Prototype Bucket Design

This design was not verified due to the Prototype Frame and Prototype Drive subsystem testing. The design, however, was believed to have insufficient stiffness and robustness for digging and accidents.

The new design was driven by the requirements of being sturdy let light weight. In order for the Digger Arm subsystem to effectively collect and deposit the most simulant in one trip, the bucket must be of minimal weight. The following were the additional key driving requirements pertaining to the design of the Bucket subsystem.

- The Bucket shall dig with at least 22 kPa at the tip of the bucket
    - Requirement derived from regolith simulant technical paper [7]
- The collected regolith shall not cause the rover to tip forward
- The bucket shall pitch forward at least 145 degrees with respect to the horizontal
- The bucket actuator shall support no more than 500 lbs

After the architectural design of the subsystem had been laid out, trade studies were performed and critiqued according to the system and bucket subsystem requirements. The primary focus of the trade studies dealt with medium to large scale front end loader components such as the Bobcat loader bucket seen in Fig 23.

Figure 23: Bobcat Loader Bucket [8]

The trade studies proved not feasible as a direct solution, thus leading to the design of a custom bucket. The operation of a front end loader was also observed, providing valuable insight into the design of a bucket system. The use of teeth, maximum pitch angle, and actuator position on the bucket were observed in operation and taken into account during the design process. Teeth increase the pressure at the digging point, thus reducing the amount of force needed to penetrate the surface of the simulant. The bucket design was to imitate that which industry has already proven, only on a smaller scale.

A decision matrix was used to determine how the remaining requirements would be satisfied. The bucket decision matrix can be seen in Table D.2 in Appendix D. The results of the decision matrix indicated that an aluminum bucket with a sub frame would best suit the bucket design based on the derived requirements. The actuator attachment to the bucket was designed based on front end loader observations, the required pitch angle, and maximum available force from the bucket actuator. The available digging force was calculated to ensure it met the derived requirement. The results of the process consisted of a bucket made of aluminum sheet metal with an aluminum sub frame, steel cutting blade with teeth, 8020 compatible interfacing components, and placement of the actuator approximately 3" from the bottom pivot. The Solid Edge CAD assembly of the bucket can be seen in Fig. 24.

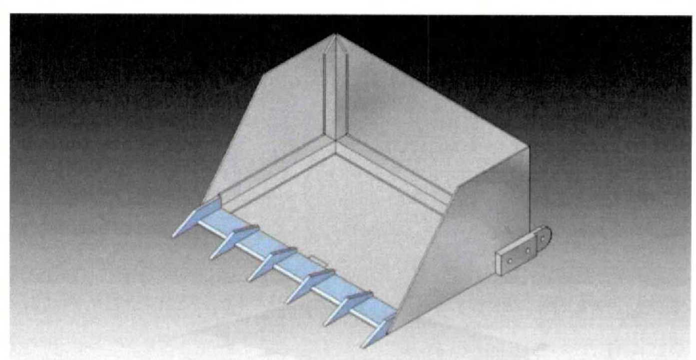

Figure 24: Bucket Design

The physical dimensions, weight, Digger Arm interface, and Pitch angle of the bucket design were

verified using Solid Edge, and the actuator forces are in the process of being verified using Working Model. The Bill of Materials for the Bucket System can be found in Table E.3 of Appendix E.

Control Communication System:

The driving requirements for the electrical subsystem were:

- The CC subsystem shall interface with NASA's wireless network
- The excavator system shall be remotely controlled
- The CC subsystem shall provide enough power for at least 15 minutes

The product hierarchy, seen in Fig 25, was developed after analyzing the requirements imposed on the CC subsystem.

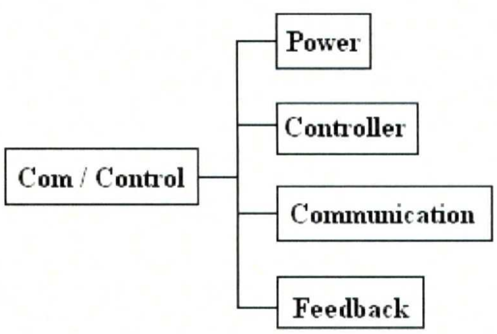

Figure 25: Control Communications Product Hierarchy

The two systems that comprise the total electrical system are the base station and the teleoperated vehicle. The base station consists of a laptop with the necessary Python software installed and an internal wireless modem capable of connecting to an external wireless network. The vehicle's electrical system consists of a WiPort evaluation board that receives control commands wirelessly and passes them on to an Arduino Mega microcontroller. The Arduino Mega interprets the received serial commands and formats them according to the Sabertooth motor controller specifications. These commands are then sent to one of three Sabertooth motor controllers, which control and provide power to the drive and digging systems. A 12V battery provides power for the WiPort Board, wireless camera, and Arduino Mega, while two 24V batteries in parallel provide power for the motor controllers and thus the driving and digging systems.

The electrical system implemented in the prototype lunar regolith excavator used a XBee wireless module to enable communication between the laptop base station and a Serializer robot controller. Relatively simple text control commands were interpreted by the Serializer and either used to control one of two onboard H-bridges or a Devantech MD22 motor controller via a single I2C interface. The address system used in I2C interfaces ensured that additional motor controllers could be added to the system should mechanical design changes require more motors.

While the prototype electrical system did allow for the remote operation and control of the excavator, several severe limitations soon surfaced during testing. The Serializer's two onboard H-bridges, while useful, were limited by both the relatively low 12V, 2A limit imposed by the Serializer's design. Since the actuators chosen by the mechanical team were rated for a maximum current draw of 2.9A during a full stall condition, this meant that the possibility of causing permanent damage to the electronics during regular operation was significant. Also, the analog ports on the Serializer were input-only. This design limitation forced the team to select an I2C motor controller that was less than ideal, as no other way of communicating with an outside board could be found. The XBee module was an extremely convenient means of communicating with the vehicle, but the XBee system is designed to function as an ad-hoc, point-to-point wireless network. The LMC rules state that all communication between vehicle and base station must pass through NASA's onsite wireless network. As there was no way of using the XBee modules on this network, major network design changes were required. But perhaps the strongest argument against the prototype electrical system was the software required to communicate with the Serializer and thus the rest of the vehicle. The Serializer robot controller is not an open-source platform, and all programming must be done with the use of Visual

C++ and Microsoft Robotics Developer Studio software libraries provided by the manufacturer. As no team members were familiar with Visual C++, the Robotics Developer Studio libraries and thus development environment was used. However, the libraries had not been updated to function with the newest version of the development environment. This caused many problems with implementing features such as rear collision detection and automated arm control. The software was also found to respond somewhat erratically to gamepad joystick input, resulting in erratic and sometimes total loss of vehicle control.

The final excavator electrical system is similar in functionality to the prototype but features a much more versatile and reliable set of components. In place of the XBee modules, a Lantronix WiPort evaluation board is used to connect the vehicle to an onsite wireless network and relay serial commands between base station and vehicle. Since the WiPort board also has several onboard general purpose digital pins, it is used to remotely trigger relays that control the power to the rest of the vehicle. This functionality allows for remote powering on and off of the vehicle, which is required in the 2010 LMC rules. Also capable of controlling vehicle power is a red emergency stop button mounted on the rear of the vehicle. The WiPort board passes all serial command signals to an Arduino Mega microcontroller. The Arduino Mega receives analog sensor data from a Sharp GP2D120 IR rangefinder and sends control commands to one of three Sabertooth 2x10 motor controllers. The IR rangefinder has a reliable proximity detection range of between 4cm and 22cm, which is enough to provide ample warning of a rear collision. Each Sabertooth motor controller is capable of providing up to 24V and 8A to two DC motors, which is more than enough to power the four drive motors and two linear actuators that are used in the vehicle. A Linksys wireless video camera provides the operator with a live video feed of the excavator's surroundings, enabling true remote operation. The motor controllers are powered by two 24V batteries wired in parallel, and the rest of the electronics are powered by a single 12V battery.

As per the rules given out by NASA, the excavator must be remotely controlled and receive start/stop signals through the NASA WiFi network. In order to accomplish this, the design process was implemented in the design of a software system for the excavator. The purpose of the software system is to provide control to and feedback from the excavator remotely. To ensure that the software system provided these services while following the competition rules given by NASA, the design was based off a set of user requirements. After enumerating the requirements, the decisions about what framework to use and how to layout the software system. A simple schematic of the system can be seen in Fig 26.

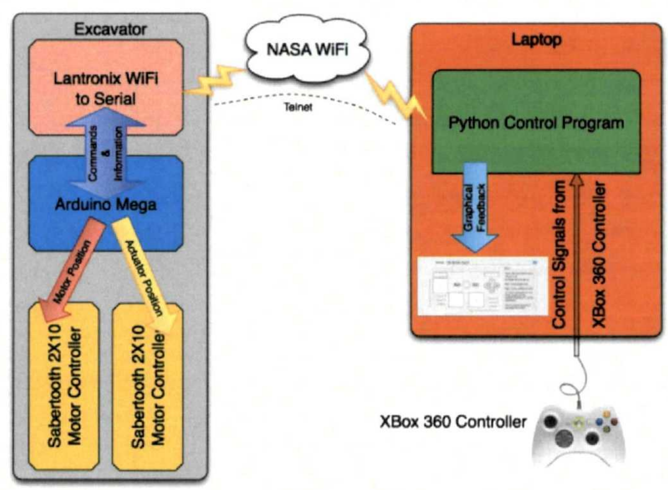

Figure 26: Software Schematic

The requirements that the software system adheres to is based on the rules given by NASA and by other requirements imposed by the team. These are the requirements that the software system adheres to:

- All communication shall travel over NASA's WiFi network
- All data communication shall not exceed 5Mbps
- The excavator shall be remotely started and killed
- The excavator shall be remotely controlled using a gamepad or joystick
- Information from the excavator shall be displayed (voltage, backup obstacle detection, etc...)

In order to facilitate serial communication over a WiFi network, the Lantronix WiPort device was selected as the gateway for communications to and from the Arduino Mega. The data transfer budget was rationed between the WiFi webcam and the connect to the Lantronix, but the communication between the computer and the Lantronix WiPort is negligible. The Lantronix board has some general purpose I/O ports that we will use to control the remote start and kill functions. The Input from the gamepad or joystick will be translated into a format that the Arduino Mega understands and sent from the Laptop to the Lantronix and ultimately the Arduino Mega from the Control Software. Any information collected from the Arduino Mega will be published to the Lantronix, which relays that information to the Control Software which then processes the information and displays it to the user.

The Lantronix WiPort board was selected to facilitate the communication of serial data over the NASA WiFi link. The Lantronix achieves this by connecting to a preconfigured WiFi access point and setting up a telnet server. Telnet is simple a legacy modem protocol, allowing us to easily send asynchronous serial data over a TCP socket. Basically the Lantronix board allows for transparent communication with the Arduino as if it were connected via USB. Conveniently the Lantronix will also allow us to enable/disable power to the excavator via the NASA WiFi as well. This is accomplished by sending a specially formatted UDP data packet to the Lantronix which instructs it to set certain Digital I/O pins to High or Low states. Using this feature we will set a pin High in order to enable a relay controlling power to the electronics, and conversely setting it Low to disable power flow to the excavator electronics.

Now that a solution had been found for WiFi connection the control software needed to be designed and implemented. The Control Software has several main functions:

- Manage connections to the Lantronix WiPort
- Send the enable/disable command to the Lantronix WiPort
- Translate Input from the gamepad or joystick into commands
- Send commands to the Arduino Mega via the Telnet server on the Lantronix WiPort
- Display any information the Arduino Mega sends back

In order to accomplish this goal the software framework needed to be able to fulfill these requirements:

- Connect to the Excavator via TCP/IP Telnet (Lantronix)
- Connect to the Excavator via USB (Serial via direct connection to the Arduino)
- Interface with gamepads and joysticks
- Operate under Graphical User Interface Environment
- Easy to use / Rapid Development (short development time)
- (optional) Cross-platform compatible (Windows, Mac OS X, Linux) development time)
- (optional) Display streaming video from the WiFi webcam

After reviewing the requirements the decision was made to use the Python (2.6.x) programming language to develop the Control Software due to the fact that it is easy to use, supports Telnet, supports Serial, supports Simple GUI's, supports interfacing with gamepads and joysticks, and is cross-platform compatible. Additionally the pygame library was chosen to facilitate the GUI and gamepad/joystick interfacing. In order to communicate through a Serial port the pySerial library is also required.

In testing, the redesigned electrical system performed exactly as expected. The two battery systems were more than capable of powering the onboard electronics for the necessary 15 minutes, and the WiPort board can be configured to connect to any wireless network. Once that connection was made, sending control commands to the Arduino Mega resulted in no unexpected behavior whatsoever. This was a significant improvement over the unreliable Serializer board and associated software used in the prototype vehicle.

<u>Verification and Validation:</u>

The verification for the Team Pumpernickel's project began with the prototype excavator. It underwent frame and drive modification as well as

Frame and Drive subsystem integration. The prototype excavator verification of system requirements as defined by the Lunabotics Mining Competition Rule Book took place on Engineering Day at Auburn University, and the results involved the design a new excavator based heavily on solving the problems experienced in the prototype's verification.

Solid Edge was used for the physical verification (weight, dimensions, etc.) of components and for the integration of components into subsystems. The subsystems were then assembled into a system and verified against the system requirements as defined by the Competition Rule Book. The resulting excavator system Solid Edge CAD assembly can be seen in Fig. 27.

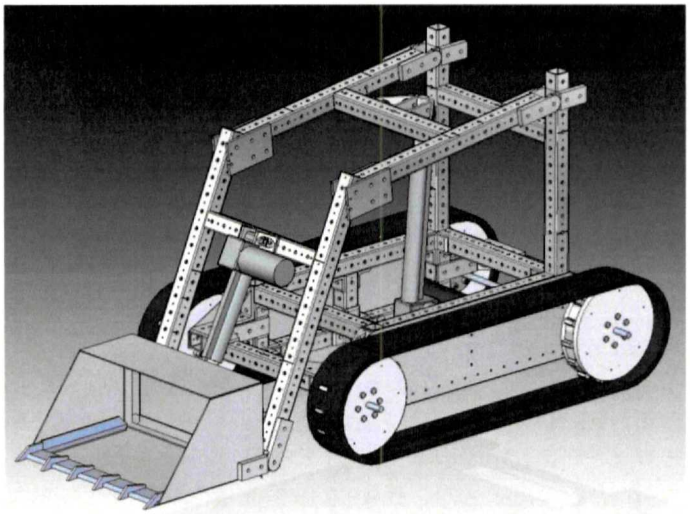

Figure 27: System Solid Edge Verification

FEMAP express, Working Model, and hand calculations were used to test the deflection and force/load requirements on each subsystem are met.

The Frame, Drive, and Com/Control subsystems have begun system integration and the verification of subsystem requirements. The remaining subsystems and excavator system have not been verified at this time. A check list of remaining tasks before system verification can be found in Appendix F. The plan for system verification includes:

Resource Budgets:

One crucial part of any design is how the technical resources are distributed. This project had three designated technical resource budgets in weight, power, and data transfer rate. A technical resource budget was derived and can be seen in Table G.1 of Appendix G.

Risk Management:

The Excavator system that was created is a high risk system. The subsystems were designed around the basic necessities needed to fulfill requirements in an attempt to keep the overall weight and design time of the excavator to a minimum. Table H.2 of Appendix H shows examples of components that are not mission critical and the associated risk involved with each component as per *Chapter 2: Systems Engineering Risk Management guidelines* [3].

CONFIGURATION MANAGEMENT:

In today's engineering world computers are almost always involved in the design of systems and the solution of problems. One of the results of this is there are many computer files created during the design of a system such as a lunar excavator. One of the struggles is how to best organize and index all of these files so that all members are aware of their places. This is commonly referred to as configuration management and is a common problem in today's workplace, even outside of engineering. In order to keep all of the files created throughout this project several different techniques were used. There was a common drive provided by the school that all members had access to so this served as the main storage point for all files. Each member had an individual file on this drive where they would keep the work that they were currently working on; once the file was completed it was moved into a file corresponding to the subsystem it belonged to. Also once a new file was uploaded, if it was replacing an older version the older version was renamed and saved in an additional folder under that subsystem specifically for older designs. This was done so that in the event a new design did not work the old design could easily be reinstated. However since this drive was only accessible from a school computer a way to easily share current files needed to be found and implemented, the website dropbox.com provided this capability for this project. This site was used for

sharing files while members were away from campus. Through using both of these services and the explained organizational structure no problems with configuration management were experienced throughout the design process of the excavator.

PROJECT MANAGEMENT:

Management Structure:

The Management structure, seen in Fig 28, for this project was similar to that of real world project in that there was a systems engineer who oversaw the whole project, then there where both mechanical and electrical engineering project leads followed by mechanical and electrical engineers.

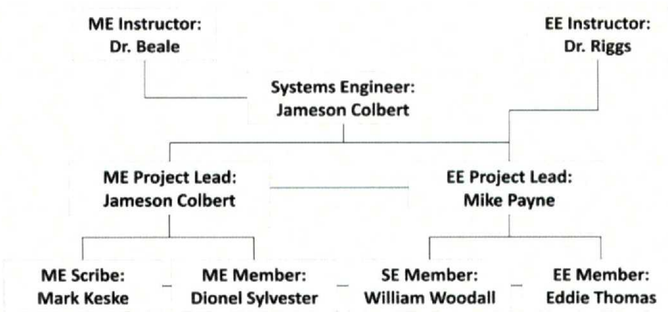

Figure 28: Management Structure Diagram

Schedule:

As is with every project, the excavator had a timeline for completion that must be met in order to complete the mission statement. This timeline was established by all of the members at the onset of this semester and has been altered to add new tasks when needed. Each subsystem had its own schedule for completion and an accompanying Gantt chart; those may be found in Appendix I. The Gantt chart for this semester may also be found in Appendix I.

Financial Budget:

One of the key factors in any project is the financial budget; with the economy in its current state money is something that is always important to keep a close eye on. This project is no different; the group was given a project budget at the beginning of the semester. One of the tasks assigned to the systems engineer was to ensure that the money was being spent properly and that the project stayed under budget. A copy of the budget can be found in Appendix J.

DELIVERABLES:

In order to ensure that each task is being completed and being done in accordance with the schedule each team member was required to provide a contract of deliverable (COD) at the onset of each process he began. The COD was then signed by the team member, the system engineer, and the instructor. These were graded assignments for each student so if the contract was not fulfilled then the student's grade would suffer from it. CODs were written for a wide variety of tasks from placing orders for parts to constructing the entire frame. CODs are attached in Appendix K to show how they were written and implemented into this project.

CONCLUSION:

Prototype Evaluation:

The first task that was undertaken by the team was to evaluate the prototype and establish a baseline of performance so that it could be improved upon. The team used Engineering Day 2010 at Auburn University for verification purposes of the prototype and it was at such time that the team designated that the design was inadequate to complete the mission statement. For this purpose the design process was initiated for a new excavator design.

New Excavator Design:

As shown in the context of this paper the design process was instituted on a system, subsystem, and component level to best ensure that the team arrived at the optimal design that met all the requirements.

System Verification/Validation:

Every installed subsystem and/or component has been verified to date. The verification process will continue until the team departs for Orlando and compete in the competition, which will serve as the system launch.

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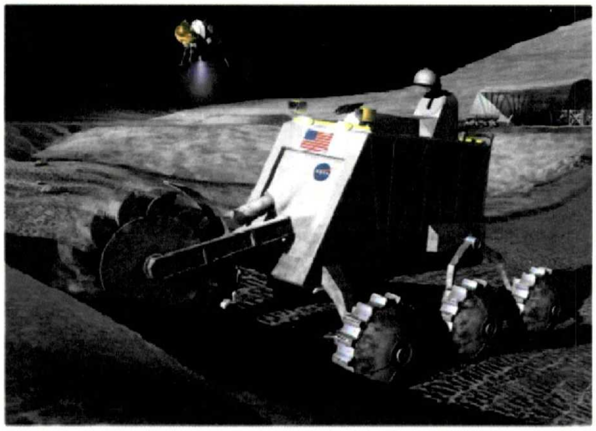
APPENDIX A: Lunabotics Mining Competition Rules

Lunabotics Mining Competition Rules

May 25-28, 2010

Kennedy Space Center

Astronaut Hall of Fame



Introduction

NASA's Lunabotics Mining Competition is designed to promote the development of interest in space activities and STEM (Science, Technology, Engineering, and Mathematics) fields. The competition uses excavation, a necessary first step towards extracting resources from the regolith and building bases on the moon. The unique physical properties of lunar regolith and the reduced 1/6th gravity, vacuum environment make excavation a difficult technical challenge. Advances in lunar regolith mining have the potential to significantly contribute to our nation's space vision and NASA space exploration operations.

The competition will be conducted by NASA at Kennedy Space Center. The prize funding for the Lunabotics Student Mining Competition is provided by NASA. The teams that can use telerobotic or autonomous operation to excavate the most lunar regolith simulant within a 15-minute time limit will win the competition. The minimum excavation requirement is 10.0 kg, and the excavation hardware mass limit is 80.0 kg. Winners are eligible to receive first, second, or third prize of $5,000, $2,500, and $1,000, respectively.

Undergraduate and graduate student teams enrolled in a U.S. college or university are eligible to enter the Lunabotics Mining Competition. Design teams must include: at least one faculty or industry advisor with a college or university affiliation and two or more undergraduate or graduate students. Teams will compete in up to five categories including: on-site mining, systems engineering paper, outreach project, slide presentation (optional), and team spirit (optional). Additionally, collaboration between a majority and minority serving institutions, digital video footage, and multidisciplinary teams earn teams additional points toward the Joe Kosmo Award for Excellence.

Prizes include monetary scholarships, a school trophy or plaque, individual certificates, KSC VIP launch invitations, and up to $1,500 travel expenses for each team member and one faculty advisor to participate with the NASA Desert RATS as the winners of the Joe Kosmo Award for Excellence.

Scoring rubrics and prize details are available at www.nasa.gov/lunabotics.

Game Play Rules

1) These rules and specifications may be subject to future updates by NASA at its sole discretion.

2) Teams will be required to perform 1 official competition attempt using lunar regolith simulant, sandbox and collector provided by NASA. NASA will fill the sandbox with compacted lunar regolith simulant that matches as closely as possible to the lunar regolith described in the Lunar Sourcebook: A User's Guide to the Moon, edited by G. H. Heiken, D. T. Vaniman, and B. M. French, copyright 1991, Cambridge University Press. NASA will randomly place 3 obstacles and create 2 craters on each side of the sandbox. Each competition attempt will occur with 2 teams competing at the same time in opposite directions, 1 on each side of the sandbox. After each competition attempt, the obstacles will be removed, the lunar regolith simulant will be returned to a compacted state, and the obstacles will be returned to the sandbox. See the Sandbox Diagrams on page 6.

3) In the official competition attempt, the teams that acquire (and deliver into the collector container) the first, second, and third most mass by excavating lunar regolith simulant over the minimum excavation requirement (10 kg) within the time limit (15 minutes) will respectively win first, second, and third place prizes. In the case of a tie, the teams will compete in a head-to-head round, where the team that acquires the most lunar regolith simulant in that round wins.

4) All excavated mass deposited in the collector during the official competition attempt will be weighed after completion of the competition attempt. Any obstacles deposited in the collector will be removed from the lunar regolith simulant collected.

5) The excavation hardware shall be placed in the randomly designated starting zones. The order of teams will be randomly chosen throughout the competition.

6) A team's excavation hardware shall only excavate lunar regolith simulant located in that team's respective mining zone at the opposite end of the sandbox from the team's starting zone. The team's exact starting point and transversal direction will be randomly selected immediately before the competition attempt.

7) The excavation hardware is required to move across the obstacle zone to the mining zone and then move back to the collector box to deliver the simulant into the collector box. See the Sandbox Diagrams on page 6.

8) Each team is responsible for placement and removal of their excavation hardware onto the lunar regolith simulant surface without the use of a ramp. There must be 1 person per 23 kg of mass of the excavation hardware, requiring 4 people to carry the maximum allowed mass. Assistance will be provided if needed.

9) Each team is allotted a maximum of 10 minutes to place the excavation hardware in its designated starting position within the sandbox and 5 minutes to remove the excavation hardware from the sandbox after the 15-minute competition attempt has concluded.

10) The excavation hardware operates during the 15-minute time limit of the competition attempt. The 15-minute time limit will be reduced if a team is not ready at the team's competition attempt start time. Time will start even if a team is still setting up their excavator after the 10 minute setup time period has elapsed. The competition attempt for both teams in the sandbox will end at the same time.

11) The excavation hardware will end operation immediately when the power-off command is sent, as instructed by the competition judges.

12) The excavation hardware cannot be anchored to the lunar regolith simulant surface prior to the beginning of the competition attempt.

13) Each team will be permitted to repair or otherwise modify the excavation hardware after the team's practice time. The excavation hardware will be inspected the evening before the competition takes place and quarantined until just before the team's competition attempt.

Field Rules

14) At the start of the competition attempt, the excavation hardware may not occupy any location outside the defined starting zone. At the start of each competition attempt the starting location and direction will be randomly determined.

15) The collector box top edge will be placed so that it is adjacent to the side walls of the sandbox without a gap and the height will be 1 meter from the top of the simulant surface directly below it. The collector top opening will be 1.65 meters long and .48 meters wide. See the Sandbox Diagrams in the Definitions. A target may be attached to the collector for navigation purposes only. This navigational aid must be attached during the setup time and removed afterwards during the removal time period. The mass of the navigational aid is included in the maximum excavation hardware mass limit of 80.0 kg and must be self-powered.

16) There will be 3 obstacles placed on top of the compressed lunar regolith simulant surface within the obstacle zone before the competition attempt is made. The placement of the obstacles will be randomly selected before the start of the competition attempt. No obstacles will be buried in the simulant. Each obstacle will have a diameter of approximately 20 to 30 cm and an approximate mass of 7 to 10 kg. Obstacles placed in the collector will not be counted as part of the excavated mass. There will be 2 craters of varying depth and width, being no wider or deeper than 30cm.

17) Excavation hardware must operate within the sandbox: it is not permitted to pass beyond the confines of the outside wall of the sandbox and the collector during the competition attempt. The regolith simulant must be collected in the mining zone allocated to each team and deposited in the collector. The team may only dig in its own mining zone. The simulant must be carried from the mining zone to the collector by any means. The excavator can separate intentionally, if desired, but all parts of the excavator must be under the team's control at all times. Any ramming of the wall may result in a safety disqualification at the discretion of the judges. A judge may disable the excavator by pushing the red emergency stop button at any time.

18) The excavation hardware must not push lunar regolith simulant up against the wall to accumulate lunar regolith simulant.

19) If the excavation hardware exposes the sandbox bottom due to excavation, touching the bottom is permitted, but contact with the sandbox bottom or walls cannot be used at any time as a required support to the excavation hardware. Teams should be prepared for airborne dust raised by either team during the competition attempt.

Technical Rules

20) During the competition attempt, excavation hardware is limited to autonomous and telerobotic operations only. No physical access to the excavation hardware will be allowed during the competition attempt. In addition, telerobotic operators are only allowed to use data and video originating from the excavation hardware. Visual and auditory isolation of the telerobotic operators from the excavation hardware in the Mission Control Room is required during the competition attempt. The Mission Control Room is approximately 60 meters from the sandbox. Telerobotic operators will be able to observe the sandbox through 2 fixed overhead cameras in 2 opposing corners of the sandbox through monitors that will be provided by NASA in the Mission Control Room. These monitors should be used for situational awareness only. The walls of the Mission Control Rooms are metal framed with 5/8" wall board on both sides of the framing. The sandbox will be outside the Astronaut Hall of Fame metal frame building in an enclosed tent.

21) Mass of the excavation hardware shall not exceed 80.0 kg. Subsystems on the excavator used to transmit commands/data and video to the telerobotic operators are counted towards the 80.0 kg mass limit. Equipment not on the excavator used to receive commands from and send commands to the excavation hardware for telerobotic operations is excluded from the 80.0 kg mass limit.

22) The excavation hardware must be equipped with an easily accessible red emergency stop button (kill switch) of minimum diameter 5 cm on the surface of the excavator requiring no steps to access. The emergency stop button must stop excavator motion and disable all power to the excavator with 1 push motion on the button.

23) The communications link used for telerobotic operations is required to have a total bandwidth of no more than 5.0 megabits/second. Teams will be required to demonstrate compliance prior to starting the competition attempt. Wi-Fi infrastructures will be provided and monitored by NASA: 1 for practice and 1 for the competition attempt. IP addresses will be provided and managed by NASA. Each team must request anticipated IP address requirements by March 15, 2010 by e-mailing Susan Sawyer at Susan.G.Sawyer@nasa.gov. IP address requests will be processed on January 15 and March 15, 2010. NASA anticipates a minimum of 2 IP addresses for each team. NASA technical experts will offer feedback on real-time networking performance during practice attempts. There will be no lunar latency time delay imposed on teams by NASA this year.

24) The excavation hardware must be contained within 1.5m width x .75m length x 2m height. The hardware may deploy beyond the 1.5 m x .75 m footprint after the start of the competition attempt, but may not exceed a 2 meter height. The excavation hardware may not pass beyond the confines of the outside wall of the sandbox and the collector during the competition attempt to avoid potential interference with the surrounding tent. The team must declare the orientation of length and width to the inspection judge. Because of actual lunar hardware requirements, no ramps of any kind will be provided or allowed.

25) To ensure that the excavation hardware is usable for an actual lunar mission, the excavation hardware cannot employ any fundamental physical processes (e.g., suction or water cooling in the open lunar environment), gases, fluids or consumables that would not work in the lunar environment. For example, any dust removal from a lens or sensor must employ a physical process that would be suitable for the lunar surface. Teams may use processes that require an Earth-like environment (e.g., oxygen, water) only if the system using the processes is designed to work in a lunar environment and if such resources used by the excavation hardware are included in the mass of the excavation hardware.

26) Components (i.e. electronic and mechanical) are not required to be space qualified for the lunar vacuum, electromagnetic, and thermal environments.

27) The excavation hardware may not use any process that causes the physical or chemical properties of the lunar regolith simulant to be changed or otherwise endangers the uniformity between competition attempts.

28) The excavation hardware may not penetrate the lunar regolith simulant surface with more force than the weight of the excavation hardware before the start of the competition attempt.

29) No ordnance, projectile, far-reaching mechanism, etc. may be used (excavator must move on the lunar regolith simulant).

30) No excavation hardware can intentionally harm another team's hardware. This includes radio jamming, denial of service to network, regolith simulant manipulation, ramming, flipping, pinning, conveyance of current, or other forms of damage as decided upon by the judges. Immediate disqualification will result if judges deem any maneuvers by a team as being offensive in nature. Erratic behavior or loss of control of the excavation hardware as determined by the judges will be cause for immediate disqualification.

31) Teams must submit documentation containing a description of the excavation hardware, its operation, potential safety hazards, a diagram, and basic parts list. Each team will deliver the team's written documentation in .pdf by April 15, 2010 to Susan.G.Sawyer@nasa.gov.

32) Teams must submit video documentation containing no less than 30 seconds of excavation hardware operation and at least 1 full cycle of operation. One full cycle of operations includes excavation and depositing material. Each team will deliver their video documentation by May 10, 2010 to Susan.G.Sawyer@nasa.gov. This video documentation is solely for technical evaluation of the team's excavation hardware. It is not for the video category in the overall Lunabotics Mining Competition. Video specifications:

    Formats/Containers: .avi, .mpg, .mpeg, .ogg, .mp4, .mkv, .m2t, .mov; Codecs: MPEG-1, MPEG-2, MPEG-4 (including AVC/h.264), ogg theora; Minimum frame rate: 24 fps; Minimum resolution: 320 x 240 pixels

Definitions

Collector – A device provided by NASA for the competition attempt into which each team will deposit excavated regolith simulant. The collector will be large enough to accommodate each team's excavated regolith simulant. The collector will be stationary and located adjacent to the sandbox. Excavated regolith simulant mass will be measured after completion of the competition attempt. The collector mass will not be counted towards the excavated mass or the mass of the excavation hardware. The collector will be 1.65 meters long and .48 meters wide. The collector walls will rise to an elevation of 1 meter above the regolith simulant surface directly below the collector. See the Sandbox Diagrams on page 6.

Competition attempt – The operation of a team's excavation hardware intended to meet all the requirements for winning the competition by performing the functional task. The duration of the competition attempt is 15-minutes.

Excavated mass – Mass of the excavated lunar regolith simulant delivered to the collector by the team's excavation hardware during the competition attempt, measured in kilograms (kg) with official result recorded to the nearest one tenth of a kilogram (0.1 kg).

Excavation hardware – Mechanical and electrical equipment, including any batteries, gases, fluids and consumables delivered by a team to compete in the competition.

Functional task – The excavation of regolith simulant from the sandbox by the excavation hardware and deposit from the excavation hardware into the collector box.

Lunar regolith simulant – Specific lunar regolith simulant provided by NASA during the competition attempt is to be determined. The simulant will have a particle size and distribution similar to the lunar regolith as stated in the Lunar Sourcebook: A User's Guide to the Moon, edited by G. H. Heiken, D. T. Vaniman, and B. M. French, copyright 1991, Cambridge University Press. Teams are encouraged to develop or procure simulants based on lunar type of minerals and lunar regolith particle size, shape, and distribution.

Minimum excavation requirement – 10.0 kg is the minimum excavated mass which must be met in order to qualify to win the competition.

Power – All power shall be provided by a system onboard the excavator. No facility power will be provided to the excavator. There are no power limitations except that the excavator must be self-powered and included in the maximum excavation hardware mass limit of 80.0 kg.

Practice time – Teams will be allowed to practice with their excavators in the sandbox on May 25 and 26, 2010. NASA technical experts will offer feedback on real-time networking performance during practice attempts.

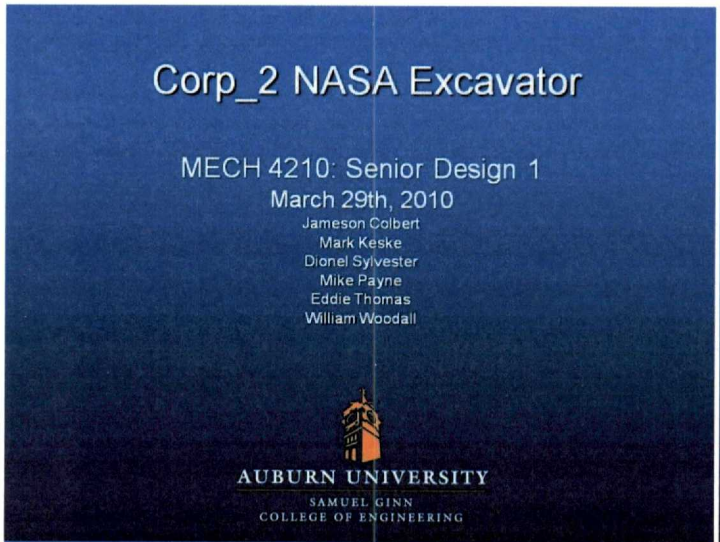
Reference point – A fixed location on the excavation hardware that will serve to verify the starting location and traversal of the excavation hardware within the sandbox. An arrow on the reference point must mark the forward direction of the excavator in the starting position configuration. The judges will use this reference point and arrow to orient the excavator in the randomly selected direction and position.

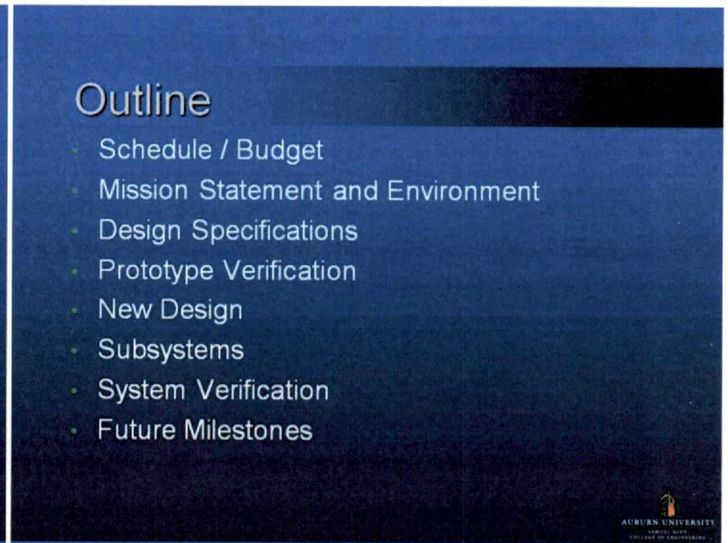
Sandbox – An open-topped container (i.e., a box with a bottom and 4 side walls only), containing regolith simulant, within which the excavation hardware will perform the competition attempt. The inside dimensions of the each side of the sandbox will be 7.38 meters long and 3.88 meters wide, and 1 meter in depth. A dividing wall will be in the center of the sandbox. The sandbox for the official practice days and competition will be provided by NASA. See the Sandbox Diagrams on page 6.

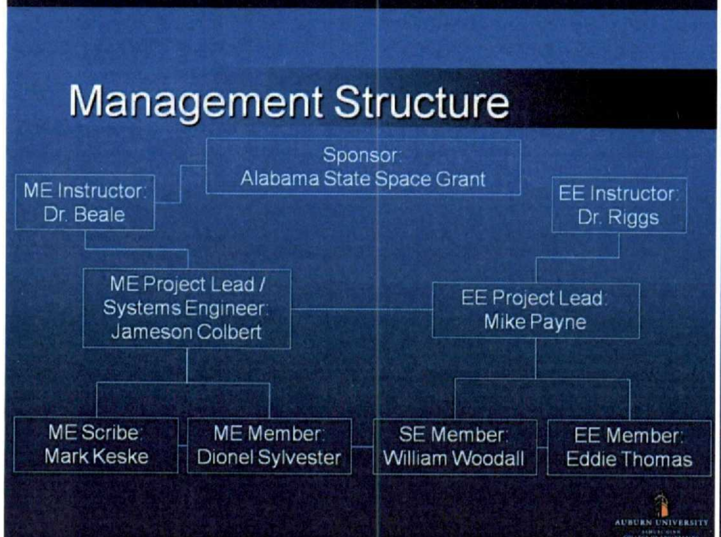
Telerobotic – Communication with and control of the excavation hardware during the competition attempt must be performed solely through the provided communications link which is required to have a total bandwidth of no more than 5.0 megabits/second on all data and video sent to and received from the excavation hardware.

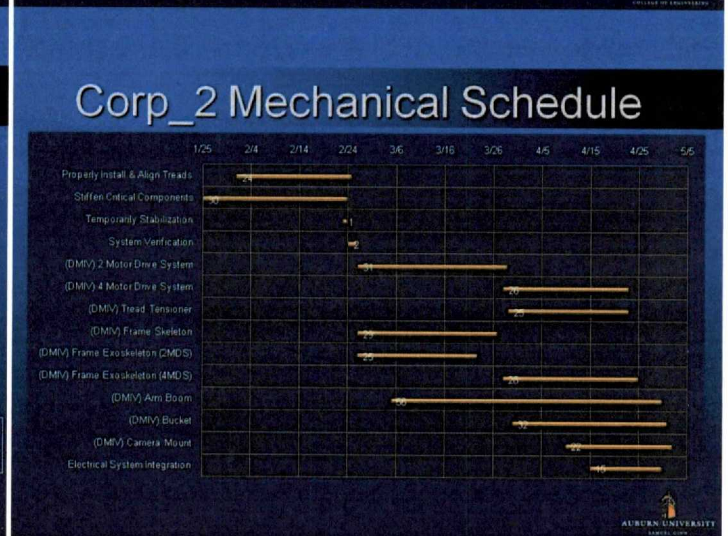
Time Limit – The amount of time within which the excavation hardware must perform the functional task, set at 15 minutes; set up excavation hardware, set at 10 minutes; and removal of excavation hardware, set at 5 minutes.

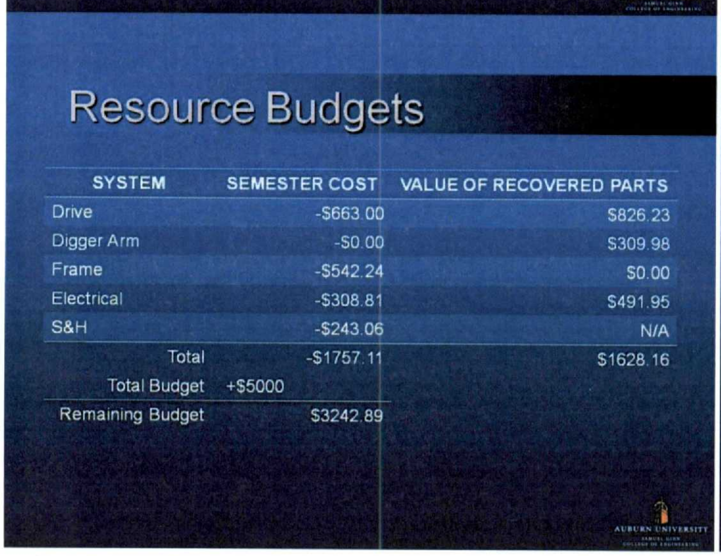
APPENDIX B: Preliminary Design Review

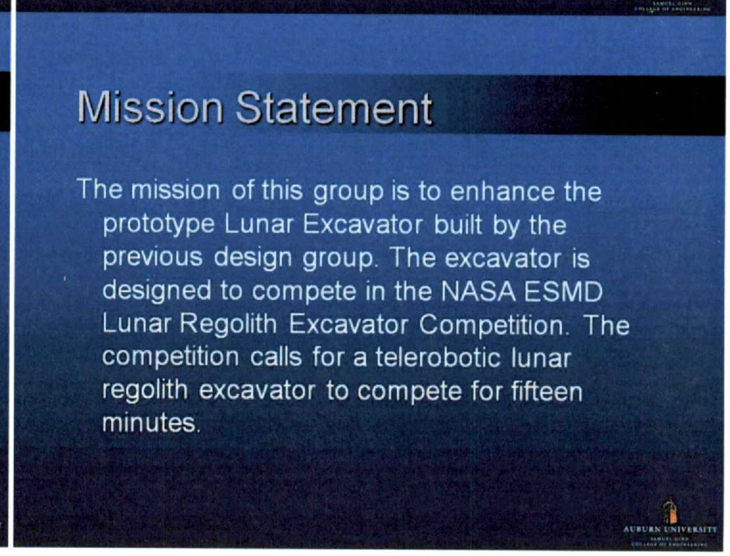












Mission Environment

The environment of operation for the excavator is theoretically the surface of the moon, however for competition purposes the environment will be a simulated lunar surface in a controlled climate on site at the Kennedy Space Station in Orlando, FL.

Design Requirements

MECHANICAL

- Must weigh under 80kg
- Must have an original footprint of less than .75m x 1.5m x 2m
- Components must be applicable to semi-lunar surfaces
- Must be able to dump soil into collection bin 1m above surface

ELECTRICAL

- Must be autonomous or telerobotic.
- Data limit of 5Mb/s
- Must have accessible emergency stop
- Does not have to be space rated

Mechanical Concepts of Operations

- Loader bucket designed to collect soil.
- Excavator will transport collected soil to a collection bin.
- Excavator will deposit collected soil in said collection bin.
- Excavator will be able to avoid and/or move obstacles in its path.

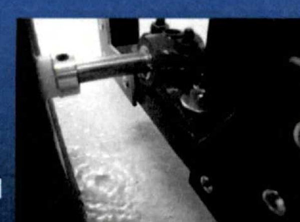
Electrical Concepts of Operations

- Batteries will provide power for 15mins of operation time
- Excavator will be controlled remotely via NASA's wireless network
- Operator will be able to independently control motors and actuators

Prototype

Prototype Frame Issues

- Thin wall carbon fiber tube frame deflections
  - Bending
  - Torsion
  - Compression
- Garolite (G-10) side panel deflections
  - Flat sheet bending



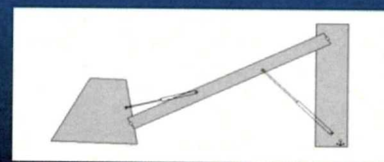
Tube frame deflecting under compression from bolts

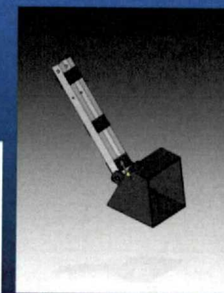
Prototype Drive Issues

- Motors directly mounted to side panel
- Motors directly mounted to wheels
- Tracks wouldn't stay on
- Bearing mount deflection
- Drive wheel mounting inadequate for proper power transmission

Prototype Arm Issues

Problems
- Slow
- Unstable



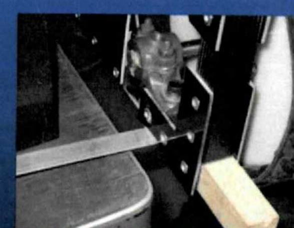


Prototype Electrical Issues

- Serializer
  - Produced erratic control
  - Software flexibility extremely limited
- AC inverter unnecessary for operation
- XBee not permitted per competition rules
- Devantech motor controller inadequate

Prototype Frame Alterations

- Replacement of 1/8" G-10 side panels with 1/8" 6061 aluminum sheet metal
- Additional aluminum front cross member
- Solid inserts for thin wall carbon fiber tube
- Temporary arm stabilization



Additional member and solid insert

Prototype Drive Alterations

- Motor mounts installed
- Side panel replaced
- Track tensioner installed
- Drive hubs installed

Prototype Validation (E-Day)

- Could only turn on slick surfaces
- Bucket arm TOO SLOW
- Bucket arm experiencing high deflections
- Frame fracture at bearing mounts
- Excavator was outside of competition dimensions
- Batteries did not provide cold cranking amps needed
- Serializer produced uncontrolled movement

Re-Design of Excavator

- Similar Architectural Design
  - Track drive system
  - Front-end loader design
- Salvaged Parts
  - Motors
  - Actuators
  - Lantronix WiPort board
  - E-Stop

Modified Derived Requirements

Mechanical

- Rigid Frame
- Increased turning torque
- Increase digger arm speed
- Increase rigidity of arm to frame interface
- Increase effectiveness of bucket

Electrical

- Control commands sent over wireless network
- More versatile onboard microcontroller

Physical Decomposition

Tele-Operated Lunar Excavator

- Excavate Regolith
- Transport Regolith
  - Digger Arm
    - Excavate: 3-Link Mech Bar Bucket
    - Transport: Rigid Bucket
  - Frame
    - Rigid Design
    - Open Access
    - 8020 Skeleton
    - Aluminum Panels
  - Drive
    - Track System
    - Chain & Sprocket
- Telerobotic Operation
  - Vision
    - Wifi Camera
  - Control
    - Game Controller
    - WiPort Board
    - Arduino Mega
    - Sabertooth 2x10

Interfaces

INTERFACE	SOLUTION	INTERFACE	SOLUTION
Mech to Mech		**Elec to Mech/ Elec**	
Frame to Drive	Bearing Mounts	Controller to Motors	Sabertooth 2x10 MC
Frame to Digger Arm	Rigid Vertical Posts	Controller to Actuators	Sabertooth 2x10 MC
Mech to Mech/Elec		**Elec to Elec**	
Frame to Motors	Side Panel Mounts, Motor Mounts	Batteries to Electronics	Fuse Buss (in fabrication)
Frame to Actuator	Hinged Mount	Camera to Controller	Wireless Network
Drive to Motors	Chain & Sprocket System	Base Station to Excavator	WiPort Board
Digger Arm to Actuator	Hinged Mount	Operator to Base Station	Game Controller
Mech to Elec		Network to Motor Controllers	Arduino Mega
Frame to Batteries	Rigid Mount	Batteries to Relay	Emergency Stop
Frame to Control Board	Rigid Mount		
Frame to Camera	Custom Arm (to be manufactured)		

New Frame Design

- Modified Derived Requirements
  - The new frame must be rigid
  - The new frame must account for maximum total system dimensions specified by the competition rules
  - The new frame must interface with the other Excavator subsystems

Design Decisions

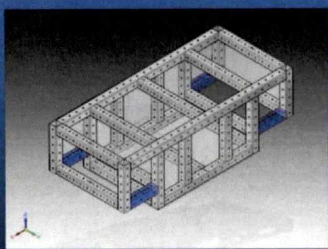
Influencing Factors

- Aluminum vs. Steel
  - Extra 8020
  - Ease of fabrication
- Interfacing between Drive and Arm system
  - 8020
- Past Prototype

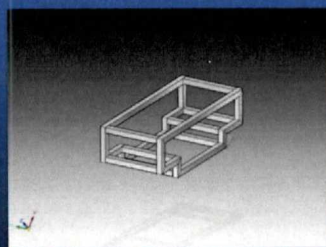
Trade Studies

SuperDroidRobots HD2 Treaded Tank Robot

Possible Frame Designs



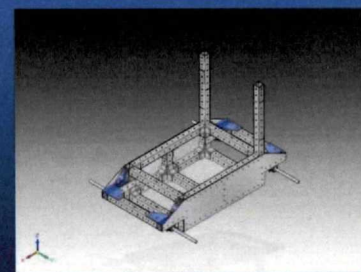
Full Box Frame



Welded Frame

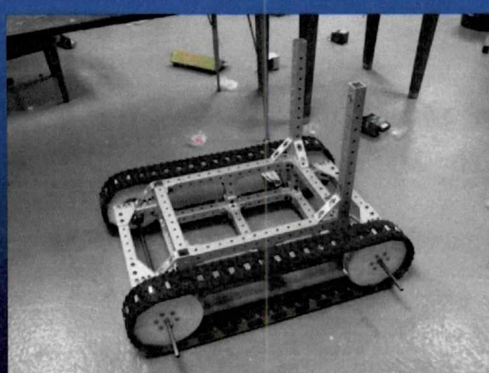
Frame Design

- Rigid frame
  - Drive and Digger Arm interface
- Able to support loads more than 80 kg
- Lighter than Full Box design
- Simpler Fabrication than Welded design



Frame Design

New Frame Verification



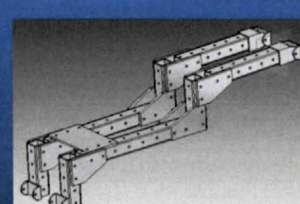
New Drive Design

- Mod Derived Requirements
  - Must be able to turn effectively in grass
  - Interface between drive and frame subsystems must be rigid
  - Treads must be capable of staying for 20 minutes of continuous use

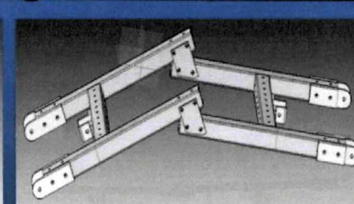
New Drive Design

- Turn Effectively
  - Chain drive w/ 3:1 reduction to increase torque
- Interface Rigidity
  - Motor mounts
  - Solid shafts
  - Split bearings
  - Sleeve bushings in wheels
- Treads remain in place
  - Correctly dimensioned center to center dimension
  - Tensioning system (in design)
    - Waiting for verification & evaluation of current system

New Arm Design Concepts



- Faster Speed
- More Parts
- Lower Dumping Height



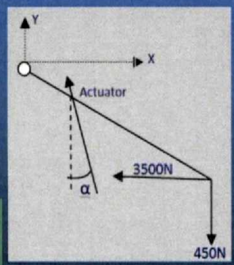
- Faster Speed
- Less Parts
- Taller Dumping Height

New Arm Specs

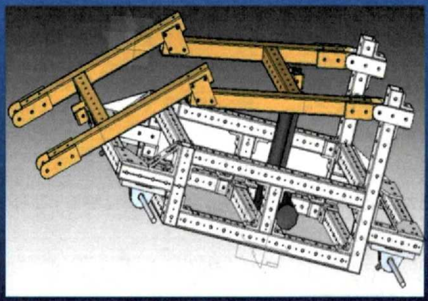
Velocity of New Concept Arm		
x(m) position from pivot	ω	Velocity(mm/s)
0.2	0.0400	31.48

Velocity of Original Arm		
x(m) position from pivot	ω	Velocity (mm/s)
0.42	0.0190	15.47
0.44	0.0182	14.76

Force Needed from Actuator for 80kg body carrying 100lbs in Bucket	
x(m) position from pivot	Force(N) at 0° angle
0.2	6021.04



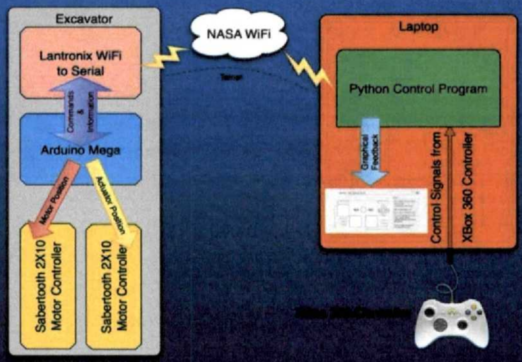
Proposed Arm Verification



New Electrical System Design

- WiPort Board
  - Receives control signals from base station
  - Provides remote start capability with relay control
- Arduino Mega
  - Converts control signals and passes them to Sabertooth motor controllers
  - Receives IR rangefinder signal and alerts operator of obstacles behind the excavator
- Sabertooth 2x10
  - Controls up to two 10A motors or actuators per board

New Software Control Design



Future Milestones

- Systems Engineering Documentation
- 4 Motor DMIV
- Arm MIV
- Bucket DMIV
- Vision System DMIV
- Electronic System Integration DMIV

APPENDIX C: Subsystem Interfaces

INTERFACE	SOLUTION	INTERFACE	SOLUTION
Mechanical to Mechanical		**Electrical to Mechatronic**	
Frame to Drive	Bearing Mounts	Controller to Motors	Sabertooth 2x10 MC
Frame to Digger Arm	Rigid Vertical Posts	Controller to Actuators	Sabertooth 2x10 MC
Mechanical to Mechatronic		**Electrical to Electrical**	
Frame to Motors	Side Panel Mounts, Motor Mounts	Batteries to Electronics	Fuse Buss
Frame to Actuator	Hinged Mount	Camera to Controller	Wireless Network
Drive to Motors	Chain & Sprocket	Base to Excavator	WiPort Board
Digger Arm to Actuator	Hinged Mount	Network to Motor Controllers	Arduino Mega
Mechanical to Electrical		Batteries to Relay	Emergency Stop
Frame to Batteries	Rigid Mount		
Frame to Control Board	Rigid Mount		
Frame to Camera	Custom Arm		

APPENDIX D: Decision Matrices

Table D.1: Frame Material Decision Matrix

	8020	Steel	Importance
Material Feature			
Rigidity / Strength	4.5	5	5
Ease of Interface	5	4	4
Cost	5	4	4
Use of Fasteners	1	4	3
Ease of Fabrication	5	3	4
Use of salvaged parts	5	1	5
Total	110.5	86	

Importance: 1 = Negligible, 5 = Significant
Material Capability: 1 = Poor, 5 = Excellent

Table D.2: Bucket Subsystem Decision Matrix

	Steel	Sheet Al	Body on Frame	Importance
Property				
Rigid / Strength	5	2	3.5	4
Weight	1	5	4.5	5
Fab/ Install Ease	4.5	4	3.5	2
Total	34	41	43.5	

Importance: 1 = Negligible, 5 = Significant
Material Capability: 1 = Poor, 5 = Excellent

APPENDIX E: Bill of Materials

Table E.1: Frame Subsystem Bill of Materials Price

*Excess parts may have been used from / for other subsystems

#	Part #	Description	UC	Q	EC	Source
1	4302	2 Hole Standard Inside Corner Bracket	$2.95	42	$123.90	8020 Inc.
2	4306	3 Hole Joining Strip	$4.40	6	$26.40	8020 Inc.
3	4332	2 Hole Inside Corner Gusset	$4.30	6	$25.80	8020 Inc.
4	4350	4 Hole 90 Degree Joining Plate	$5.60	6	$33.60	8020 Inc.
5	8973K33	3003 AL .100" thick 24" x 36"	$44.29	3	$132.87	McMaster
6	90652A030	Nylon Insert Thin 5/16-18 Hex Lock Nut pack of 100	$10.30	2	$20.60	McMaster
7	91255A581	BHSCS 5/16-18, 3/4" pack of 50	$10.36	3	$31.08	McMaster
8	92949A594	18/8 SS BHSCS 5/16-18, 3" Pack of 5	$8.42	2	$16.84	McMaster
9	9701-145	1.5" Square Tube With Holes 145"Profile	$53.65	3	$160.95	8020 Inc.
10	97447A315	AL Rivets 1/8" Dia, 1/4" Grip, pack of 250	$9.42	2	$18.84	McMaster
			Grand Total		$590.88	

Table E.2: Drive Subsystem Bill of Materials

*Excess parts may have been used from / for other subsystems

#	Part #	Description	UC	Q	EC	Source
1	1139545	M5-0.8 x 12 12.9 Socket Head Cap Screws	$7.85	1	$7.85	Fastenal
2	1688K17	PTFE-Lubricated SAE 841 Bronze Sleeve Brng for 1/2" Shaft Diameter, 5/8" OD, 1" L	$0.98	8	$7.84	McMaster
3	2299K316	Machinable-Bore Flat Sprocket for #35 Chain, 3/8" Pitch, 30 Teeth, 1/2" min Bore	$9.45	4	$37.80	McMaster
4	6261K151	Standard ANSI Roller Chain, #35, Single Strand, 3/8" Pitch, Rollerless, .2" Diameter, 10' L	$28.80	1	$28.80	McMaster
5	6359K32	Cast Iron Base Mounted Babbitt-Lined Bearing Split, for 1/2" Shaft Diameter	$42.13	8	$337.04	McMaster
6	7321K1	ANSI Roller Chain Attachment, Connecting Link Style A-1 for #35 Chain	$1.67	4	$6.68	McMaster
7	9120K15	Galvanized Low-Carbon Steel Rod 1/2" Diameter, 3' Length	$9.67	4	$38.68	McMaster
8	9946K15	Aluminum Set Screw Shaft Collar 1/2" Bore, 1" O.D., 7/16" Width	$2.05	16	$32.80	McMaster

9	NC13770	Sprocket, 35B10, 12mm Bore	$44.48	4	$177.92	Parts Town
10	TD036290	IG52-02 24V DC 290 RPM Gear Motor w/encoder	$122.80	4	$491.20	Super Driod Robots
11	TD05200	4 in. tread set	$580.63	1	$580.63	Super Driod Robots
			Grand Total		$1,747.24	

Table E.3: Digger Arm Subsystem Bill of Materials

*Excess parts may have been used from / for other subsystems

#	Part #	Description	UC	Q	EC	Source
1	4330	6 Hole 30 Degree Joining Plate	$7.10	6	$42.60	8020 Inc.
2	4345	6 Hole 45 Degree Joining Plate	$7.10	4	$28.40	8020 Inc.
3	4376	3 Hole Inside Corner Bracket	$4.15	4	$16.60	8020 Inc.
4	4390	3 Hole Pivot Plate	$11.50	12	$138.00	8020 Inc.
5	125011	12V, 7 7/8" stroke linear actuator	$149.99	1	$149.99	Northern Tool
6	125012	12V, 11 13/16" stroke linear actuator	$159.99	1	$159.99	Northern Tool
7	8910K121	Low-Carbon Steel Rectangular Bar 1/8" Thick, 2" Width, 6' Length	$18.47	1	$18.47	McMaster
8	8982K21	Multipurpose Aluminum (Alloy 6061) 90 Deg Angle, 1/8" Thick, 1" X 1" Legs, 8' Length	$12.63	2	$25.26	McMaster
9	90652A030	Nylon-Insert Extra-Wide Thin Hex Locknut Zinc-Plated Grade 2 Steel, 5/16"-18 Thread Size, Packs of 100	$10.30	1	$ 10.30	McMaster
10	91255A581	Alloy Steel Button Head Socket Cap Screw 5/16"-18 Thread, 3/4" Length, Packs of 50	$10.36	1	$10.36	McMaster
11	91259A540	Alloy Steel Shoulder Screw 1/4" Shoulder Dia, 3/4" L Shoulder, 10-24 Thread	$1.03	4	$4.12	McMaster
12	91259A626	Alloy Steel Shoulder Screw 3/8" Shoulder Dia, 1-1/4" L Shoulder, 5/16"-18 Thrd	$1.50	3	$4.50	McMaster
13	97526A404	Choose-A-Color Blind Rivet Domed, 3/16" Dia, .126"-.250" Material Thk, Gray, Packs of 100	$7.00	2	$14.00	McMaster
14	98777A213	High-Strength Zinc-Plated Steel Blind Rivet Dome, 3/16" Dia, 0.251"-0.375" Material Thickness, Packs of 25	$8.64	1	$8.64	McMaster
			Grand Total		$631.23	

Table E.4: Com/Control Subsystem Bill of Material

*Excess parts may have been used from / for other subsystems

#	Part #	Description	UC	Q	EC	Source
1	231431	10 POS 15A Termial Strip	$3.39	2	$6.78	Jameco
2	282263	15A, 24V DC relay	$7.49	2	$14.98	Jameco
3	5183T11	Blade-Style Fuse Block for 6 Atc, AF, OR Ato/257 Fuses, 32 VDC	$41.44	1	$41.44	McMaster
4	653-A22E-L-02	DP Emergency Stop (manual)	$62.23	1	$62.23	Mouser Electronics
5	7243K116	Fully Insulated Quick-Disconnect Terminal Dbl Crimp Fem, 16-14 Awg,.187" W, .02" Thk Tab, 600V	$7.36	1	$7.36	McMaster
6	7587K461	Stranded Single-Conductor Wire, UL 1015, 14 Awg, 600 VAC, Red, 100' Length	$35.16	1	$35.16	McMaster
7	7587K65	Stranded Single-Conductor Wire UL 1015, 14 Awg, 600 VAC, Black, 100' Length	$35.16	1	$35.16	McMaster
8	7964K634	Solid Single-Conductor Wire UL 1015, 22 Awg, 600 VAC, White	$10.80	1	$10.80	McMaster
9	8026K1	Modular Connector, Kit, 30 Amps at 600 VZC/VDC, Red, Packs of 5	$3.04	10	$30.40	McMaster
10	8026K1	Modular Connector, Kit, 30 Amps at 600 VZC/VDC, Black, Packs of 5	$3.04	10	$30.40	McMaster
11	855-R30-3002502	3mm metal standoffs	$0.68	50	$34.00	Mouser Electronics
12	91280A102	3mx6m Hex Screw	$5.62	1	$5.62	McMaster
13	92005A116	Metri Pan Head Phillips Machine Screw, Zinc-Plated Steel, M3 Size, 6mm Length, .5mm Pitch, Packs of 100	$2.30	1	$2.30	McMaster
14	94150A325	Metric Type 316 Stainless Steel Hex Nut M3 Size, .5mm Pitch, 5.5mm Width, 2.4mm Height, packs of 50	$2.19	2	$4.38	McMaster
15	95225A315	3M washers	$8.35	1	$8.35	McMaster
16	TE-088-210	12V 2200 mAHr NiMH 2x5 Battery Pack	$23.90	1	$23.90	Super Driod Robots
17	TE-097-320	24V 10000 mAHr NiMH Battery Pack	$259.50	2	$519.00	Super Driod Robots
18	TE-106-018	Smart Charger for 9.6V - 18V	$28.95	1	$28.95	Super Driod Robots

		NiMH and NiCad				
19	TE-106-024	Smart Charger for 19.2V - 24V NiMH and NiCad	$29.95	2	$59.90	Super Driod Robots
20	WVC2300	Cisco Wireless-G Video Camera	$359.99	1	$359.99	Cisco
21		Lantronix WiPort	$300.00	1	$300.00	
22		Sabertooth 2x10 Motor Controler	$79.99	3	$239.97	Dimension Engineering
23		Arduino Mega	$64.77	1	$64.77	Robotshops.us
24		XBox 360 controller	$49.99	1	$49.99	
			Grand Total		$1,975.83	

APPENDIX F: Project Completion / Verification Check List

- Complete Arm and Bucket Design
- Verify designs meet physical/functional requirements in Solid Edge and Working Model
- Fabricate and Assemble: Arm and Bucket Subsystems
- Integrate Arm and Bucket components into Arm/Boom subsystem
- Integrate Arm/Boom subsystem with the remaining subsystems
- Verify subsystems against interface and integration requirements
- Verify System against system requirements
- Validate System at competition

APPENDIX G: Technical Resource Budget

Table G.1: Technical Resource Budget

SOURCE		COMPONENT	ALLOTOTTED	USED
Weight			80kg	
		Frame	30kg	
		Drive	20kg	
		Arm	20kg	
		Electrical	10kg	
Power			460 Watt-hrs	
	24 V	Motor x4	300	264
		Actuator x2	154	139.2
		Motor Cntrl x3	3	1.08
		Relay x2	3	1.776
	12 V		26.4 Watt-hrs	
		WiPort	5	2.31
		Camera	15	12
		Micro-Controller	5	1.25
Transfer Rate			5 Mbps	
		Camera	2.5Mbps	750kbps
		WiPort	2.5Mbps	45kbps

APPENDIX H: Risk Management

Table H.1: Failure Classification [3]

Code	Name	Description
4	Mission Failure	If this error cannot be mitigated, the mission will be a failure – no communications to the ground station.
3	Reduced Lifetime	If this error cannot be mitigated, the mission is still a success, but further research is needed to extend mission lifetime in future missions.
2	Reduced Capability	If this error cannot be mitigated, the mission is still a success, but further research is needed to provide increased capability.
1	Non-Critical	If this error occurs, the primary mission could still be accomplished without additional need for redundancy.

Table H.2: Risk Management of Non-Mission Critical Components

Subsystem	Component	Failure/Result	Code	Mitigation
Frame				
	Nuts/Bolts	Loose Nuts/Bolts in components	2	Locking Nuts
	Side Panel Holes	Regolith entering cavity	2	Sealed Panels
	Non Critical Members	Frame deformations	3	Additional Support
	Side Panels	Crumpling / Deforming	3	Additional Support
	Bottom Panels	Crumpling / Deforming	3	Additional Support
	Battery Mount	Unrestrained batteries	2	Mount failsafe
	Controller Mount	Unrestrained controller components	2	Mount failsafe
	IR Mount	False position readings	1	Mount failsafe
	Antenna Mount	Improper signal connection	2	Mount failsafe
	Camera Mount	Lack of video feedback	3	Mount failsafe
Drive				
	Nuts/Bolts	Loose Nuts/Bolts in components	2	Locking Nuts
	Treads	Tread derails / tears	3	Four Driving Motors
	Chain for one motor	Drive chain derails	2	Chain Guard
	Drive Sprocket on one motor	Drive sprocket slips	2	Semi-Permanent Fastening
	Chain for two motors	Drive chain derails	3	Chain Guard
	Drive Sprocket for two motors	Drive sprocket slips	3	Semi-Permanent Fastening
	Motor on one side	Motor failure	3	Drive Slower
	Two Motors	Motor failure	3	Drive Slower
	Motor Mounts	Unsupported drive motors	2	Mount failsafe
Digger				

	Nuts/Bolts	Loose Nuts/Bolts in components	2	Locking Nuts
	Bucket Teeth	Tooth breaks	2	Sharp Cutting Blade
	Bucket Top	Top of bucket fractures	1	Secondary Reinforcement
Electrical				
	IR Sensor	False position reading	1	Filter
	One Battery	Limited power	3	Cells in Parallel
	Camera Battery	No video feedback	3	Cells in Parallel
	Actuators / Motors simultaneously drawing current	Limited power / Operational time	3	Individual Actuator / Motor Cells

APPENDIX I: System Schedule

Table I.1: Excavator System Schedule

System

Task	Start Date	Duration	End Date
Properly Install & Align Treads	2/1/2010	24	2/25/2010
Stiffen Critical Components	1/25/2010	30	2/24/2010
Temporarily Stabilization	2/23/2010	1	2/24/2010
System Verification	2/24/2010	2	2/26/2010
(DMIV) 2 Motor Drive System	2/26/2010	31	3/29/2010
(DMIV) 4 Motor Drive System	3/28/2010	26	4/23/2010
(DMIV) Tread Tensioner	3/29/2010	25	4/23/2010
(DMIV) Frame Skeleton	2/26/2010	29	3/27/2010
(DMIV) Frame Exoskeleton (2MDS)	2/26/2010	25	3/23/2010
(DMIV) Frame Exoskeleton (4MDS)	3/28/2010	28	4/25/2010
(DMIV) Arm Boom	3/5/2010	56	4/30/2010
(DMIV) Bucket	3/30/2010	32	5/1/2010
Electrical System Integration	4/10/2010	22	5/2/2010
System Verification	5/1/2010	20	5/21/2010

KEY
Jamie
Mark
Ray
All (See Designated Tab)

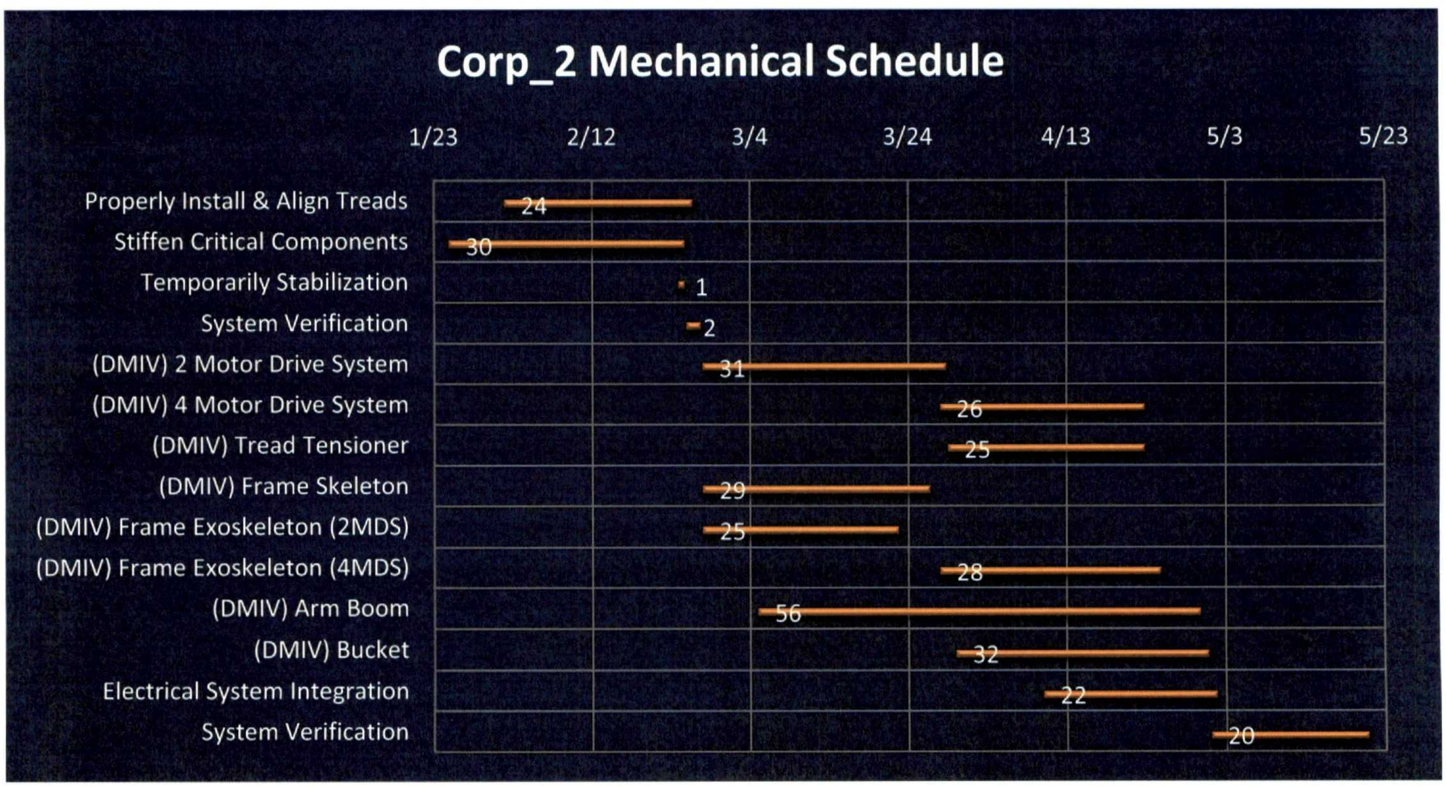


Figure I.1: Excavator System Mechanical Engineering Gantt Chart

Table I.2: Prototype Schedule

Prototype

Task	Start Date	Duration	End Date
Drive			
Properly Install & Align Treads	**2/1/2010**	**24**	**2/25/2010**
(DMI) Power Transmission Solution	2/1/2010	23	2/24/2010
(DMI) Motor Mounts	2/8/2010	7	2/15/2010
(DMI) Tensioning Apparatus	2/18/2010	5	2/23/2010
Subsystem Verification	2/15/2010	10	2/25/2010
Frame			
Stiffen Critical Components	**1/25/2010**	**30**	**2/24/2010**
(MI) Aluminum Side Panels	1/25/2010	14	2/8/2010
(MI) Inner Bracing	2/20/2010	4	2/24/2010
(DMI) Tube Frame Inserts	2/19/2010	3	2/22/2010
(MI) Additional Cross Member	2/23/2010	1	2/24/2010
Subsystem Verification	2/10/2010	14	2/24/2010
Arm			
Temporarily Stabilization	**2/23/2010**	**1**	**2/24/2010**
(DMI) Rope & Knot System	2/23/2010	1	2/24/2010
Subsystem Verification	2/23/2010	1	2/24/2010
System			
System Verification	2/24/2010	2	2/26/2010

KEY
Jamie
Mark
Ray
All

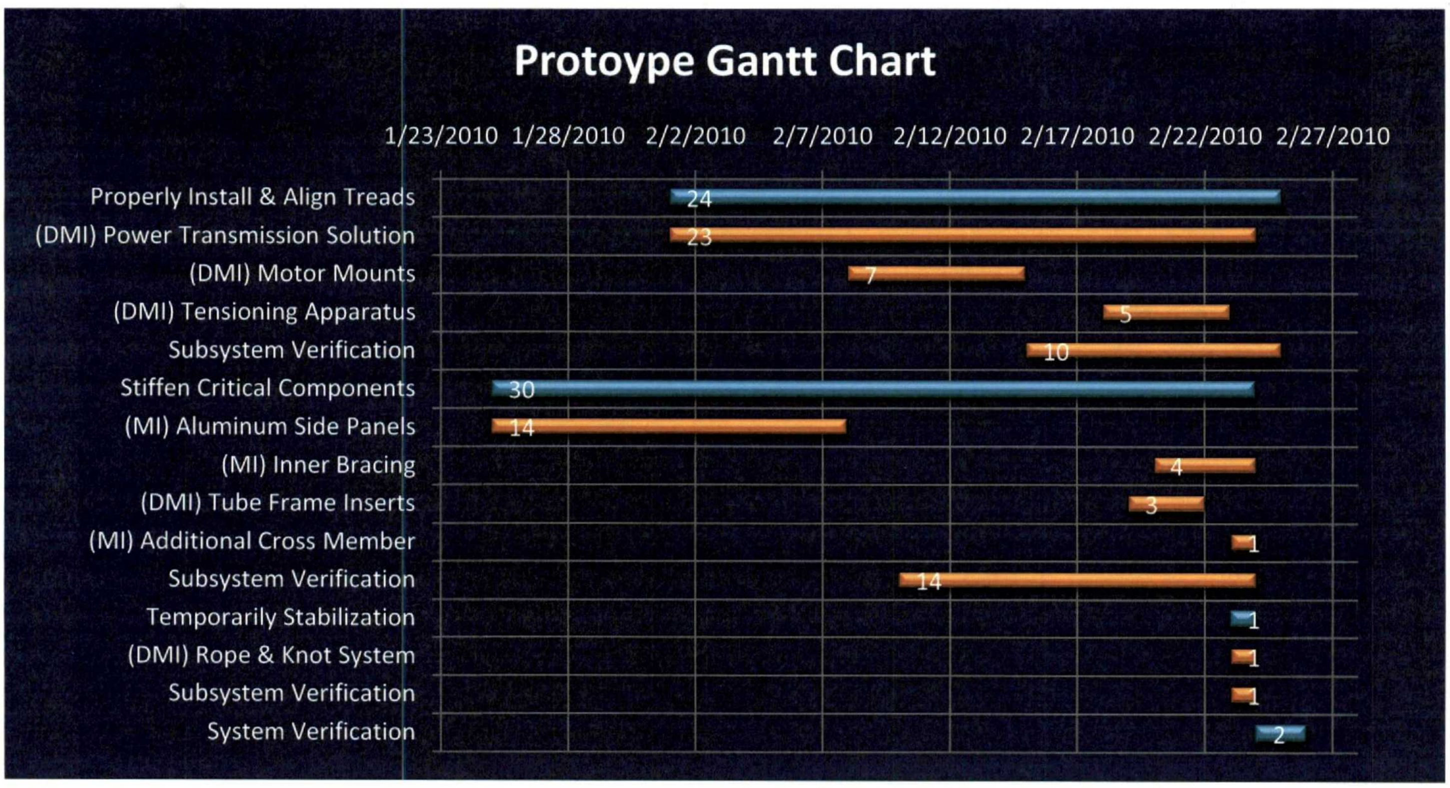


Figure I.2: Prototype Gantt Chart

Table I.3: Excavator Drive Subsystem Schedule

New Excavator Drive

Task	Start Date	Duration	End Date	
(DMIV) 2 Motor Drive System	**2/26/2010**	**31**	**3/29/2010**	KEY
Design 2MDS	2/26/2010	3	3/1/2010	Jamie
Manufacture 2MDS	3/15/2010	3	3/18/2010	Mark
Install 2MDS	3/17/2010	6	3/23/2010	Ray
Verify 2MDS	3/26/2010	2	3/28/2010	All (See Designated Tab)
(DMIV) 4 Motor Drive System	**3/28/2010**	**26**	**4/23/2010**	
Design 4MDS	3/28/2010	2	3/30/2010	
Manufacture 4MDS	4/15/2010	7	4/22/2010	
Install 4MDS	4/18/2010	6	4/24/2010	
Verify 4MDS	4/24/2010	7	5/1/2010	
(DMIV) Tread Tensioner	**3/29/2010**	**25**	**4/23/2010**	
Design TT	3/29/2010	14	4/12/2010	
Manufacture TT	4/16/2010	5	4/21/2010	
Install TT	4/20/2010	2	4/22/2010	

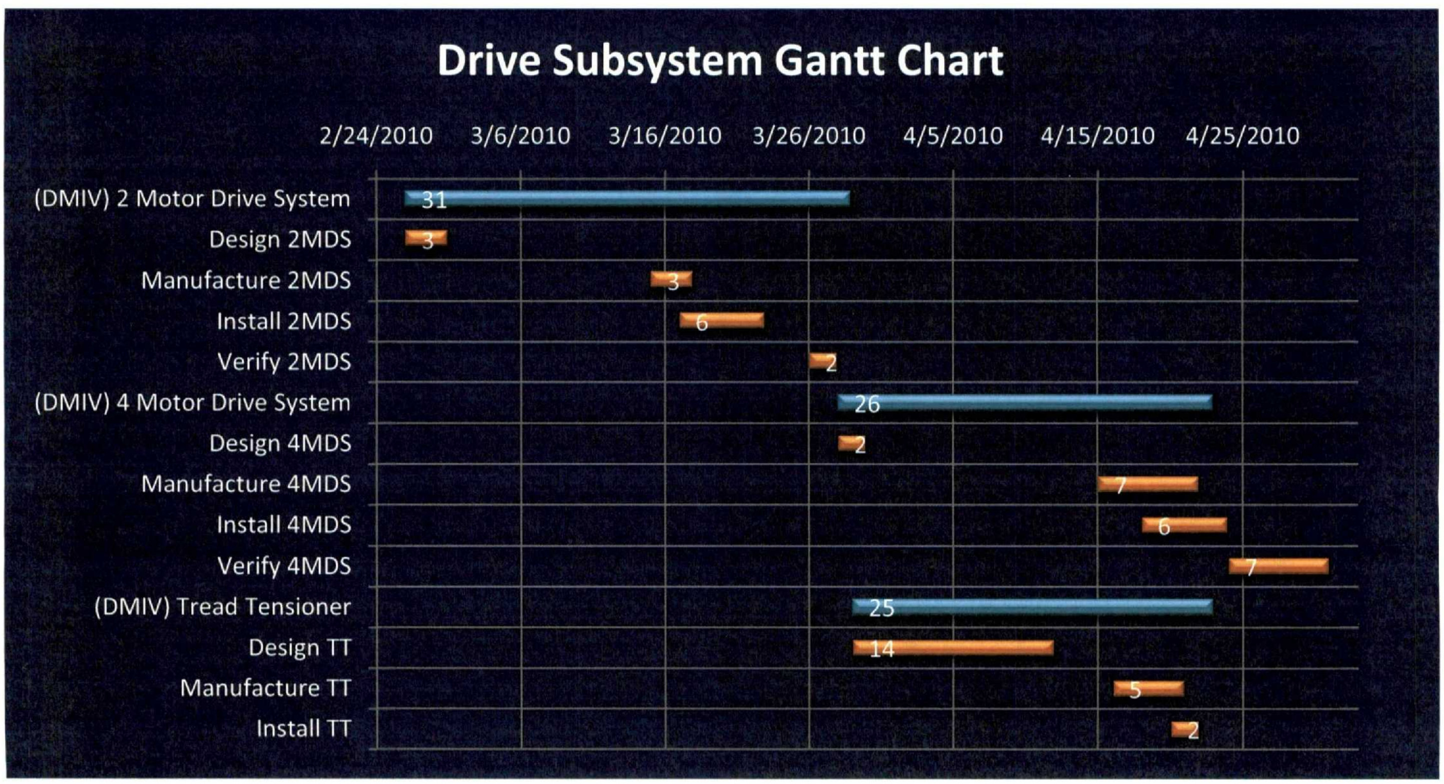


Figure I.3: Excavator Drive Subsystem Gantt Chart

Table I.3: Excavator Frame Subsystem Schedule

Frame

Task	Start Date	Duration	End Date
(DMIV) Frame Skeleton	**2/26/2010**	**29**	**3/27/2010**
Design FS	2/26/2010	12	3/10/2010
Manufacture FS	3/12/2010	3	3/15/2010
Install FS	3/14/2010	3	3/17/2010
Verify FS	3/17/2010	10	3/27/2010
(DMIV) Frame Exoskeleton (2MDS)	**2/26/2010**	**25**	**3/23/2010**
Design FE	2/26/2010	12	3/10/2010
Manufacture FE	3/11/2010	2	3/13/2010
Install FE	3/19/2010	3	3/22/2010
Verify FE	3/22/2010	1	3/23/2010
(DMIV) Frame Exoskeleton (4MDS)	**3/28/2010**	**28**	**4/25/2010**
Design FE	3/28/2010	2	3/30/2010
Manufacture FE	4/15/2010	2	4/17/2010
Install FE	4/16/2010	1	4/17/2010
Verify FE	4/24/2010	1	4/25/2010

KEY
Jamie
Mark
Ray
All (See Designated Tab)

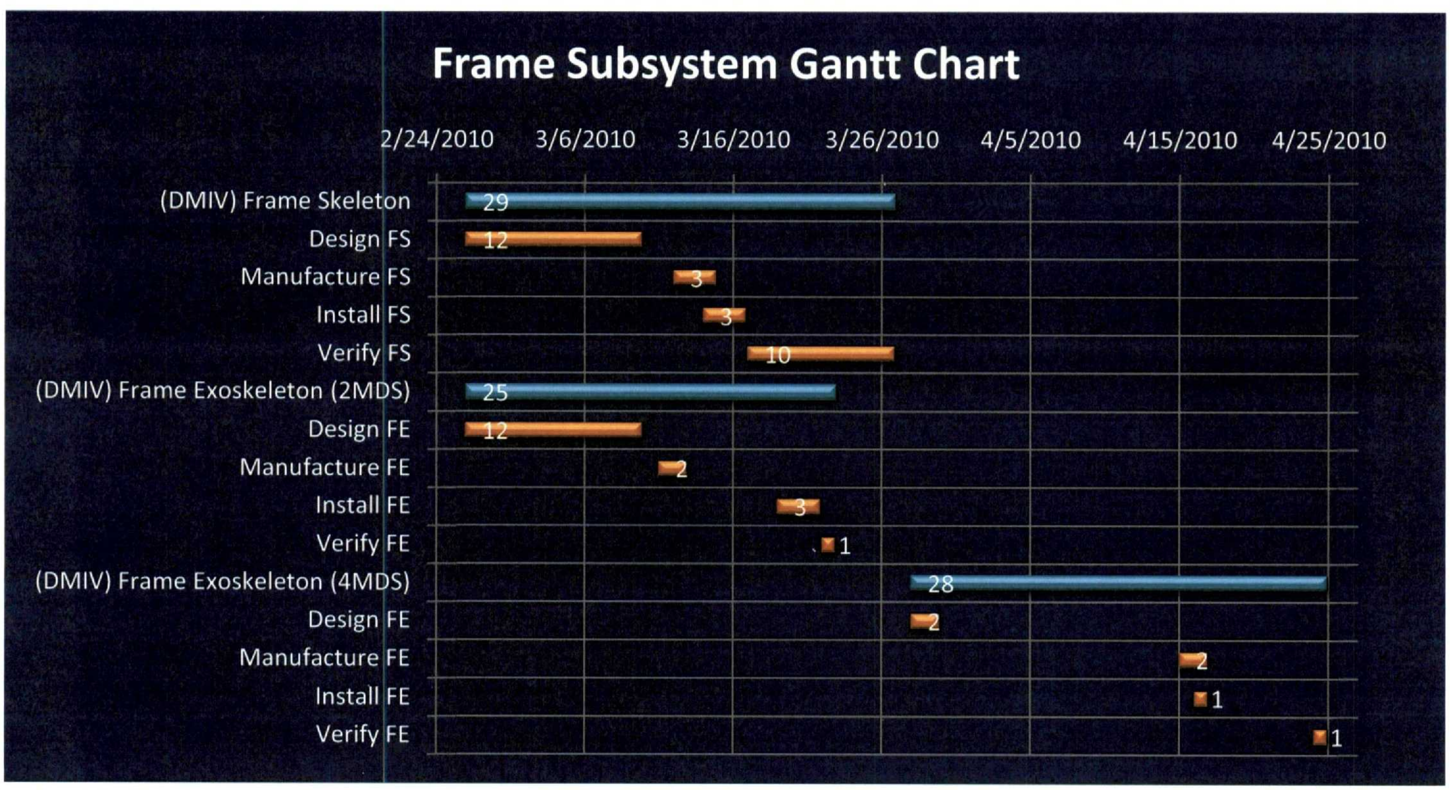


Figure I.4: Excavator Frame Subsystem Gantt Chart

Table I.3: Excavator Digger Arm Subsystem Schedule

Digger Arm

Task	Start Date	Duration	End Date
(DMIV) Arm Boom	**3/5/2010**	**56**	**4/30/2010**
Design AB	3/5/2010	40	4/14/2010
Manufacture AB	4/16/2010	4	4/20/2010
Install AB	4/18/2010	6	4/24/2010
Verify AB	4/25/2010	5	4/30/2010
(DMIV) Bucket	**3/30/2010**	**32**	**5/1/2010**
Design B	3/30/2010	14	4/13/2010
Manufacture B	4/16/2010	6	4/22/2010
Install B	4/22/2010	3	4/25/2010
Verify B	4/25/2010	6	5/1/2010

KEY
Jamie
Mark
Ray
All (See Designated Tab)

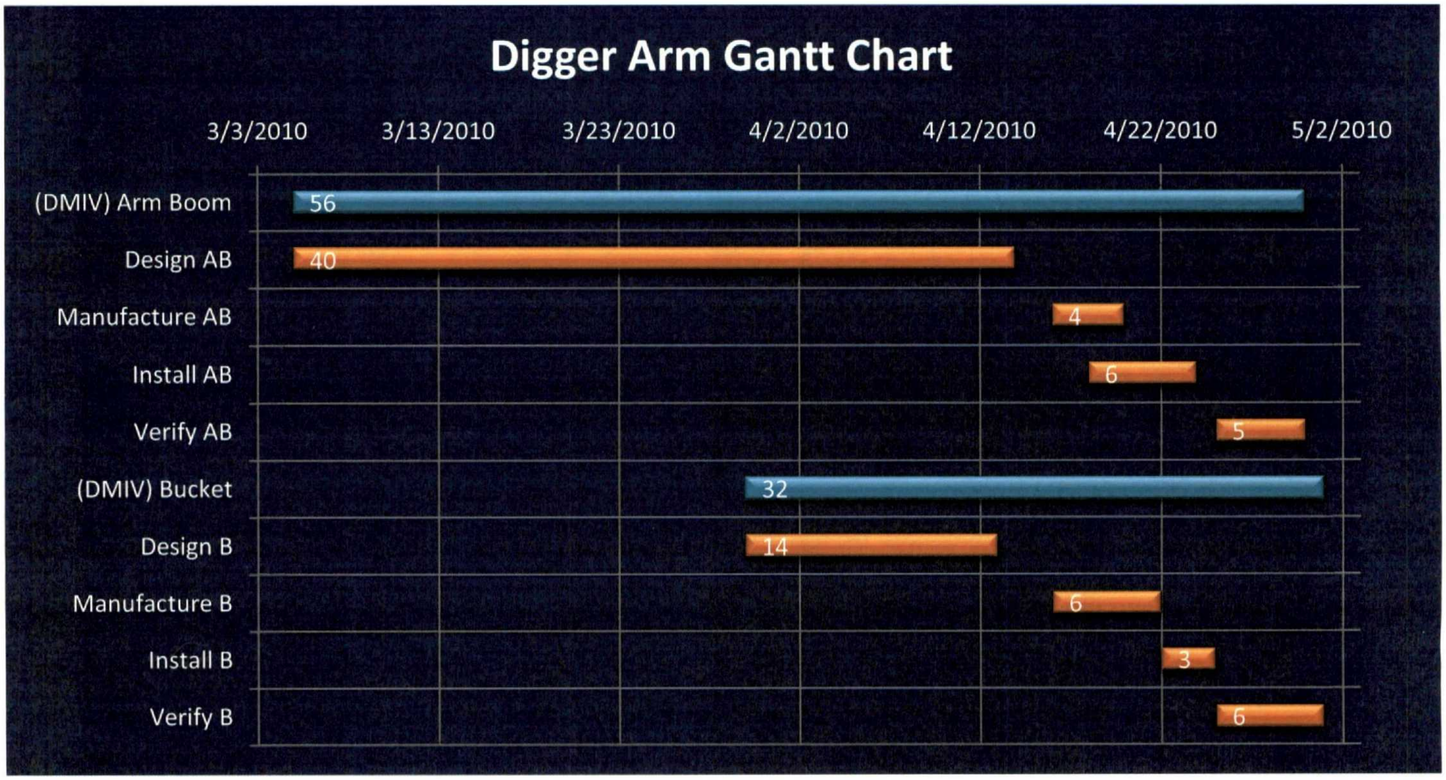


Figure I.5: Excavator Digger Arm Subsystem Gantt Chart

Table I.4: Excavator Electrical Subsystem Schedule

Electrical Subsystem

Task	Start Date	Duration	End Date
ELECTRICAL SYSTEM			
Component Selection	2/26/2010	17	3/15/2010
Power Distribution	3/3/2010	6	3/9/2010
Component Integration	3/10/2010	15	3/25/2010
Complete System Testing	3/15/2010	37	4/21/2010
Power System Wiring	3/28/2010	14	4/11/2010
Control System Wiring	4/10/2010	5	4/15/2010
Base Station Software	3/29/2010	18	4/16/2010
Arduino Programming	4/13/2010	8	4/21/2010
Control Refinements	4/20/2010	5	4/25/2010

KEY
Mike
Eddie
William
All Team Members

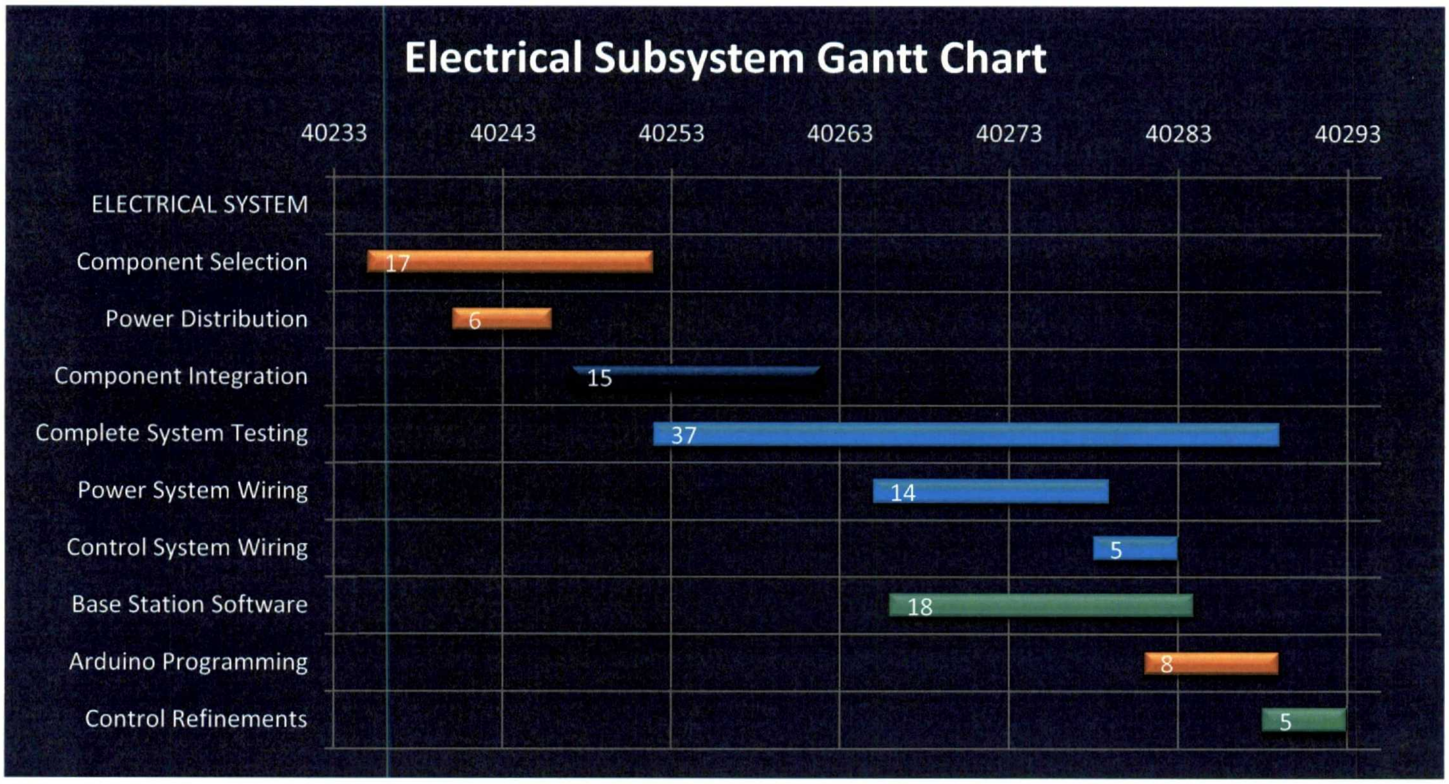


Figure I.6: Excavator Electrical Subsystem Gantt Chart

APPENDIX J: Budget

Table J: System Budget

#	Part #	Description	UC	Q	EC	Source
1	4330	6 Hole 30 Degree Joining Plate	$7.10	6	$42.60	8020 Inc.
2	4345	6 Hole 45 Degree Joining Plate	$7.10	4	$28.40	8020 Inc.
3	4376	3 Hole Inside Corner Bracket	$4.15	4	$16.60	8020 Inc.
4	4390	3 Hole Pivot Plate	$11.50	12	$138.00	8020 Inc.
5	125011	12V, 7 7/8" stroke linear actuator	$149.99	1	$149.99	Northern Tool
6	125012	12V, 11 13/16" stroke linear actuator	$159.99	1	$159.99	Northern Tool
7	8910K121	Low-Carbon Steel Rectangular Bar 1/8" Thick, 2" Width, 6' Length	$18.47	1	$18.47	McMaster
8	8982K21	Multipurpose Aluminum (Alloy 6061) 90 Deg Angle, 1/8" Thick, 1" X 1" Legs, 8' Length	$12.63	2	$25.26	McMaster
9	90652A030	Nylon-Insert Extra-Wide Thin Hex Locknut Zinc-Plated Grade 2 Steel, 5/16"-18 Thread Size, Packs of 100	$10.30	1	$10.30	McMaster
10	91255A581	Alloy Steel Button Head Socket Cap Screw 5/16"-18 Thread, 3/4" Length, Packs of 50	$10.36	1	$10.36	McMaster
11	91259A540	Alloy Steel Shoulder Screw 1/4" Shoulder Dia, 3/4" L Shoulder, 10-24 Thread	$1.03	4	$4.12	McMaster
12	91259A626	Alloy Steel Shoulder Screw 3/8" Shoulder Dia, 1-1/4" L Shoulder, 5/16"-18 Thrd	$1.50	3	$4.50	McMaster
13	97526A404	Choose-A-Color Blind Rivet Domed, 3/16" Dia, .126"-.250" Material Thk, Gray, Packs of 100	$7.00	2	$14.00	McMaster
14	98777A213	High-Strength Zinc-Plated Steel Blind Rivet Dome, 3/16" Dia, 0.251"-0.375" Material Thickness, Packs of 25	$8.64	1	$8.64	McMaster
15	1139545	M5-0.8 x 12 12.9 Socket Head Cap Screws	$7.85	1	$7.85	Fastenal
16	1688K17	PTFE-Lubricated SAE 841 Bronze Sleeve Brng for 1/2" Shaft Diameter, 5/8" OD, 1" L	$0.98	8	$7.84	McMaster
17	2299K316	Machinable-Bore Flat Sprocket for #35 Chain, 3/8" Pitch, 30 Teeth, 1/2" min Bore	$9.45	4	$37.80	McMaster
18	6261K151	Standard ANSI Roller Chain, #35, Single Strand, 3/8" Pitch, Rollerless, .2" Diameter, 10' L	$28.80	1	$28.80	McMaster
19	6359K32	Cast Iron Base Mounted Babbitt-Lined	$42.13	8	$337.04	McMaster

		Bearing Split, for 1/2" Shaft Diameter				
20	7321K1	ANSI Roller Chain Attachment, Connecting Link Style A-1 for #35 Chain	$1.67	4	$6.68	McMaster
21	9120K15	Galvanized Low-Carbon Steel Rod 1/2" Diameter, 3' Length	$9.67	4	$38.68	McMaster
22	9946K15	Aluminum Set Screw Shaft Collar 1/2" Bore, 1" O.D., 7/16" Width	$2.05	16	$32.80	McMaster
23	NC13770	Sprocket, 35B10, 12mm Bore	$44.48	4	$177.92	Parts Town
24	TD036290	IG52-02 24V DC 290 RPM Gear Motor w/encoder	$122.80	4	$491.20	Super Driod Robots
25	TD05200	4 in. tread set	$580.63	1	$580.63	Super Driod Robots
26	231431	10 POS 15A Termial Strip	$3.39	2	$6.78	Jameco
27	282263	15A, 24V DC relay	$7.49	2	$14.98	Jameco
28	5183T11	Blade-Style Fuse Block for 6 Atc, AF, OR Ato/257 Fuses, 32 VDC	$41.44	1	$41.44	McMaster
29	653-A22E-L-02	DP Emergency Stop (manual)	$62.23	1	$62.23	Mouser Electronics
30	7243K116	Fully Insulated Quick-Disconnect Terminal Dbl Crimp Fem, 16-14 Awg,.187" W, .02" Thk Tab, 600V	$7.36	1	$7.36	McMaster
31	7587K461	Stranded Single-Conductor Wire, UL 1015, 14 Awg, 600 VAC, Red, 100' Length	$35.16	1	$35.16	McMaster
32	7587K65	Stranded Single-Conductor Wire UL 1015, 14 Awg, 600 VAC, Black, 100' Length	$35.16	1	$35.16	McMaster
33	7964K634	Solid Single-Conductor Wire UL 1015, 22 Awg, 600 VAC, White	$10.80	1	$10.80	McMaster
34	8026K1	Modular Connector, Kit, 30 Amps at 600 VZC/VDC, Red, Packs of 5	$3.04	10	$30.40	McMaster
35	8026K1	Modular Connector, Kit, 30 Amps at 600 VZC/VDC, Black, Packs of 5	$3.04	10	$30.40	McMaster
36	855-R30-3002502	3mm metal standoffs	$0.68	50	$34.00	Mouser Electronics
37	91280A102	3mx6m Hex Screw	$5.62	1	$5.62	McMaster
38	92005A116	Metri Pan Head Phillips Machine Screw, Zinc-Plated Steel, M3 Size, 6mm Length, .5mm Pitch, Packs of 100	$2.30	1	$2.30	McMaster
39	94150A325	Metric Type 316 Stainless Steel Hex Nut M3 Size, .5mm Pitch, 5.5mm Width, 2.4mm Height, packs of 50	$2.19	2	$4.38	McMaster
40	95225A315	3M washers	$8.35	1	$8.35	McMaster
41	TE-088-210	12V 2200 mAHr NiMH 2x5 Battery Pack	$23.90	1	$23.90	Super Driod Robots

42	TE-097-320	24V 10000 mAHr NiMH Battery Pack	$259.50	2	$519.00	Super Driod Robots
43	TE-106-018	Smart Charger for 9.6V - 18V NiMH and NiCad	$28.95	1	$28.95	Super Driod Robots
44	TE-106-024	Smart Charger for 19.2V - 24V NiMH and NiCad	$29.95	2	$59.90	Super Driod Robots
45	WVC2300	Cisco Wireless-G Video Camera	$359.99	1	$359.99	Cisco
46		Lantronix WiPort	$300.00	1	$300.00	
47		Sabertooth 2x10 Motor Controler	$79.99	3	$239.97	Dimension Engineering
48		Arduino Mega	$64.77	1	$64.77	Robotshops.us
49		XBox 360 controller	$49.99	1	$49.99	
50	4302	2 Hole Standard Inside Corner Bracket	$2.95	42	$123.90	8020 Inc.
51	4306	3 Hole Joining Strip	$4.40	6	$26.40	8020 Inc.
52	4332	2 Hole Inside Corner Gusset	$4.30	6	$25.80	8020 Inc.
53	4350	4 Hole 90 Degree Joining Plate	$5.60	6	$33.60	8020 Inc.
54	8973K33	3003 AL .100" thick 24" x 36"	$44.29	3	$132.87	McMaster
55	90652A030	Nylon Insert Thin 5/16-18 Hex Lock Nut pack of 100	$10.30	2	$20.60	McMaster
56	91255A581	BHSCS 5/16-18, 3/4" pack of 50	$10.36	3	$31.08	McMaster
57	92949A594	18/8 SS BHSCS 5/16-18, 3" Pack of 5	$8.42	2	$16.84	McMaster
58	9701-145	1.5" Square Tube With Holes 145"Profile	$53.65	3	$160.95	8020 Inc.
59	97447A315	AL Rivets 1/8" Dia, 1/4" Grip, pack of 250	$9.42	2	$18.84	McMaster
			Grand Total		$4,945.18	

APPENDIX K: Contracts of Deliverables Examples

Contract of Deliverable

Contract Title: Prototype Motor Mount
Contract Number: MPK001
Team: Corp_2 NASA ESMD Lunabotics Mining Competition
Student Name: Mark P. Keske
Date: 18 February 2010

Task: Design, manufacture, install, and verify an internal motor mount for the prototype drive subsystem in preparation for the E-Day system verification. The motors are expected to still experience deflections large enough to cause tread derailing after the installation of an aluminum side panel (COD-C1).

The design solutions are as follows:

- Install a rigid motor mount that will be placed in between the end of the motor located inside the prototype and the inside bottom panel of the prototype. The design will consist of a u-bolt with clamping mount plate on top of a balsa wood spacer.

The manufacturing processes are as follows:

- The u-bolts and necessary hardware will be purchased. The balsa spacers will be manufactured using a cutting knife and hand operated power tools. Holes will be drilled in the bottom panel of the prototype according to desired u-bolt placement.

The installation processes are as follows:

- The motor mounts will be installed after the motors have been installed into the side panels.

The verification processes are as follows:

- The motor mount will be verified through physical deflection tests and tread alignment

The deliverables for this contract include:

- Motor Mount DMIV

Interfacing Plan: The prototype drive motor mount will be designed in accordance with the prototype frame design. The motor mount bolt holes will be placed according to the specified location of the side panel motor mount hole (COD C1). The verification of the motor mounts is dependent upon the completion of the Prototype Frame Modifications (COD C1).

Delivery Date: 26 February 2010

MARK P. KESKE
Student's Signature

Manager's Signature

____Optional______
Instructor's Signature

Figure K.1: Contract MPK001, Prototype Motor Mount

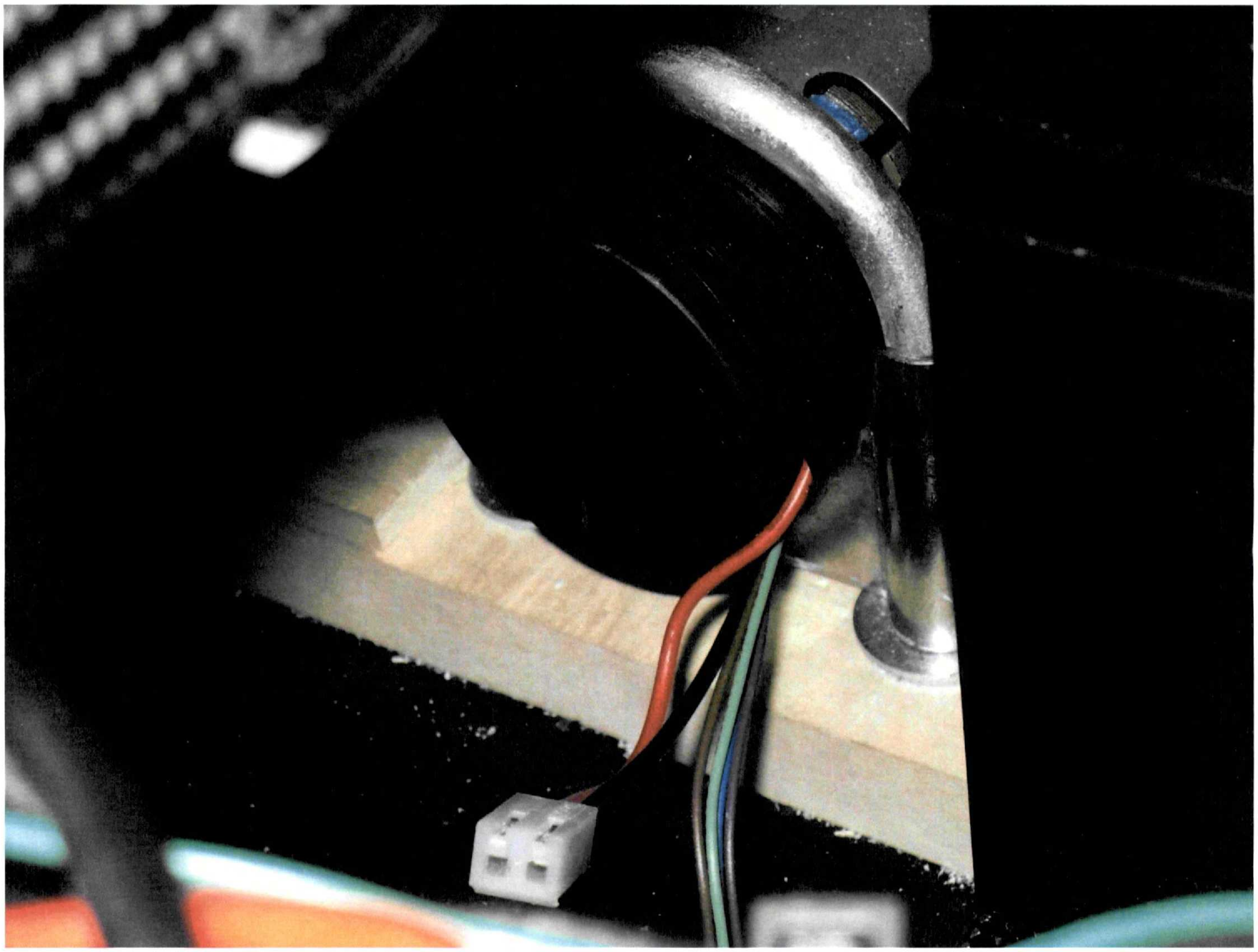


Figure K.2: Contract MPK001, Prototype Motor Mount Deliverable

Contract of Deliverable

Contract Title: Collaborative Prototype Frame Modification
Contract Number: C1
Team: Corp_2 NASA ESMD Lunabotics Mining Competition
Student Name: Jameson Colbert and Mark P. Keske
Date: 02 February 2010

Task: Design, manufacture, install, and verify prototype excavator frame modifications in preparation for the E-Day system verification. The prototype excavator frame subsystem experiences high deflections under loading from the prototype drive subsystem interface. Areas of significant importance include the G-10 Garolite side panel to which the drive motor and drive wheel are directly mounted, the hollow carbon fiber tubes to which the front wheel shafts are mounted, and the hollow carbon fiber tubes which support the tension in the treads. The location of internal cross members is also an area of importance due to drive subsystem motor mount bolt pattern (COD-MPK001).

The design solutions are as follows:

- The G-10 side panels will be replaced with 1/8" 6061 aluminum side panels in order to reduce the deflections experienced from flat plate bending.
- The hollow tube carbon fiber front members will be reinforced with internal bracing made of balsa wood in order to increase compression and torsional rigidity of the members.
- A 90 degree aluminum reinforcement member will be installed between the front left and front right members in order to provide greater bending rigidity.
- Translate internal carbon fiber cross members such that the motor mount u-bolt can be installed

The manufacturing processes are as follows:

- The aluminum side panels will be manufactured from oversized aluminum sheet metal. The overall dimensions of the side panels will be machined using the DML, and the rivet holes and motor mount hole locations will be transferred from the G-10 side panel. The holes will then be drilled to size.
- The balsa inserts will be manufactured using previous prototype mock-up material which already has the correct outer dimensions. Radii will be cut into the corners of the balsa inserts using a knife blade, and through holes will be drilled for the wheel shaft mount bolts. Channels will also be cut along the sides to provide clearance for the rivets along the inside of the frame.
- The aluminum cross member will be cut to the proper length dimension, and holes will be drilled for mounting at the wheel shaft mount.
- The internal carbon fiber cross member rivets will be drilled out. The members will then be translated, and the rivet hole locations transferred from the cross members to the bottom panel of the excavator body. The bottom panel will then be drilled to hole specification.

The installation process for the proposed design solutions are as follows:

Figure K.3.A: Contract C1, Collaborative Prototype Frame Modification

- The G-10 side panels will be removed, and the aluminum side panels will be riveted in place.
- The front wheel shaft mounts will be unbolted and removed, and the balsa inserts will be slid into place from the front of the carbon fiber tube. The wheel shafts will then be reinstalled with the bolts going through the balsa insert.
- One nut from each front wheel shaft mount will be removed, and the aluminum cross member will be mounted onto the front wheel shaft mount bolts. The nut will then be reinstalled.
- The cross members will be re-riveted in place after translation.

The verification procedure for the design solutions include:
- Side Panel verification will include FEMAP analysis of flat plate bending in aluminum vs. G-10, and physical deflection tests
- Balsa insert verification will include physical deflection tests
- Aluminum cross member verification will include physical deflection tests
- The translated cross members will be verified through mating / fitment of the drive motor mounts

The deliverables for this contract include:
- Side Panel DMIV
- Balsa Insert DMIV
- Aluminum cross member DMIV
- Translated carbon fiber V
- Frame rigidity verification through tread subsystem verification

Interfacing Plan:

The prototype frame modifications will be made in collaboration with Jameson Colbert and the prototype drive modifications. The location of the rivet and mount holes in the side panels will not be changed in order to maintain previously verified tread tension. The holes in the balsa wood inserts will be dimensioned according to the hole dimensions of the front wheel shaft mount in the drive subsystem. The holes in the aluminum cross member will be dimensioned according to the wheel shaft mount location on the frame subsystem. The location of the translated internal carbon fiber mounts will be driven by the location of the motor mount bolt holes (COD-MPK001). The side panel shall accommodate for the belt tensioner subsystem (COD-C2). The verification of the prototype frame modifications is dependent upon the completion of the drive subsystem modifications and verification.

Delivery Date: 26 February 2010

MARK P. KESR

Student's Signature

James Colbert

Manager's Signature

Optional

Instructor's Signature

Figure K.3.B: Contract C1, Collaborative Prototype Frame Modification Cont.

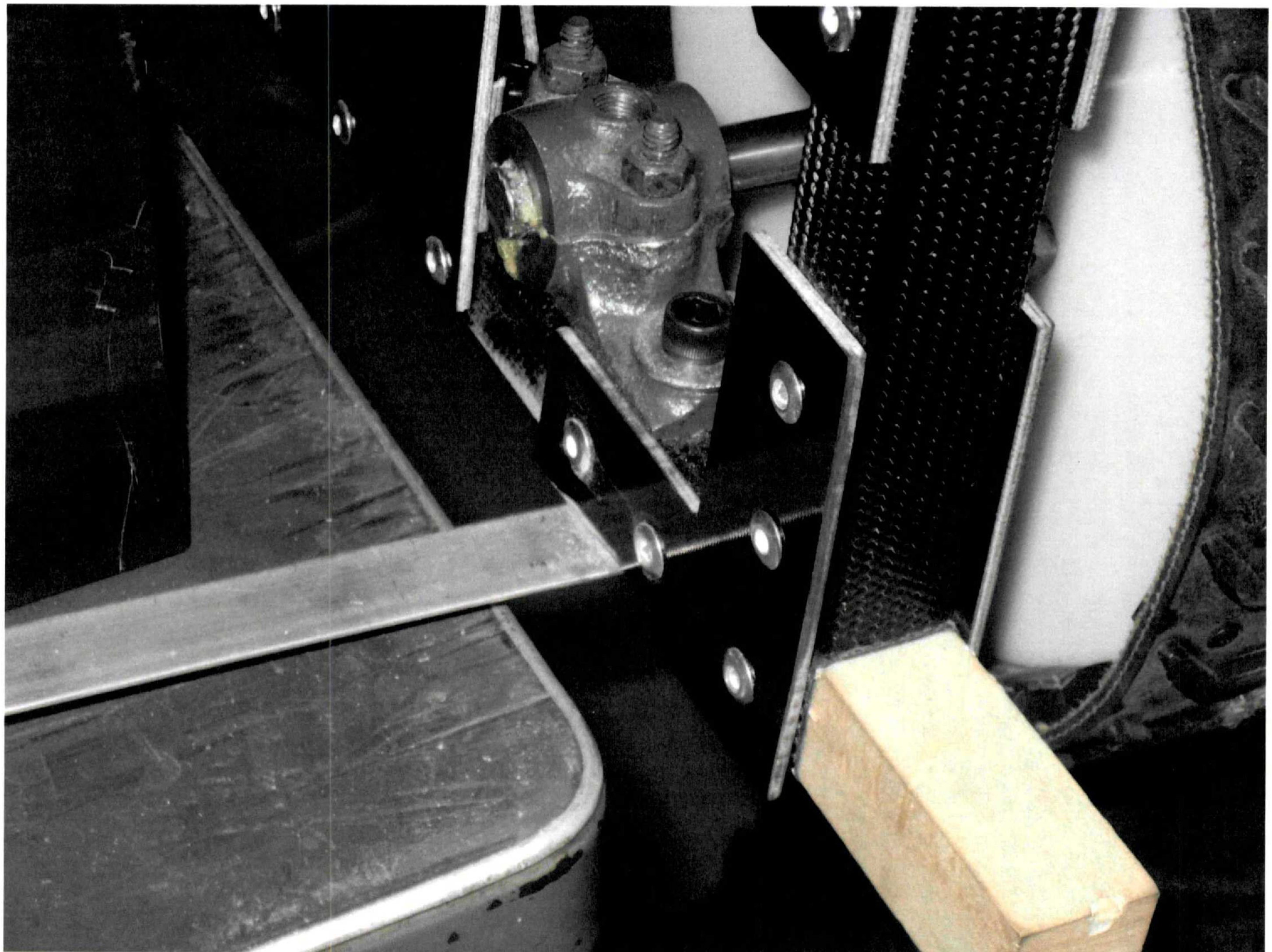


Figure K.4: Contract C1, Collaborative Prototype Frame Modification Deliverable

Contract of Deliverable

Contract Title: Collaborative Prototype Drive Component Modification
Contract Number: C2
Team: Corp_2 NASA ESMD Lunabotics Mining Competition
Student Name: Jameson Colbert and Mark P. Keske
Date: 02 February 2010

Task: Design, manufacture, install, and verify a tread tensioner and a custom motor shaft wheel hub for the prototype drive subsystem in preparation for the E-Day system verification. The prototype power transmission system failed during preliminary verification. The failure occurred in that the motor drive shaft spun freely in the drive wheel. The treads on the prototype drive subsystem were improperly tensioned causing the treads to derail.

The design solutions are as follows:

- Install a solid linkage in the form of a bolt on wheel hub between the motor drive shafts and drive wheels. The design will consist of a 12mm shaft collar welded to a flat plat with the wheel assembly bolt pattern
- Install a static idler pulley system inside the tread loop such that the idler pulley pushes up on the treads. The design will consist of a solid shaft to which the idler pulleys will be mounted. The shaft will be supported by shaft ball bearings at each end. The shaft will be mounted through the body of the excavator such that the bearings will be mounted in the hanging position from the top frame member.

The manufacturing processes are as follows:

- The 12mm shaft collars will be purchased. The square flat plate will be cut out of steel using an abrasive saw and the surface will be prepared for welding. The center of the plate will be marked and the 12mm shaft collar will be welded to the plate. The dead center of the plate is not completely necessary since the bolt pattern will be added to the flat plate after the collar is attached. The collar will be welded piecewise in order to reduce heat expansion and contraction deflections. The bolt pattern will be placed by rotating the shaft / plate on the axle of the wheel, thus scribing the bolt pattern diameter (BPD). The bolt location will be transferred onto the BDP using white out, and the holes will be drilled.
- A ½" shaft will be purchased, salvaged bearings, and salvaged idler pulleys in the form of plastic lawnmower wheels will be used. A hole will be drilled in the side panel to allow for the passing of the shaft, and two bolt holes will be drilled in the upper carbon fiber frame member for bearing mounting. The treads of the lawnmower wheels will be removed in order to obtain the desired O.D. of the idler pulley.

The installation processes are as follows:

- The wheel hubs will be first mounted onto the motor drive shafts, and then the wheels will be bolted to the wheel hubs.
- The wheel bearings will be mounted loosely in place, and the shaft will then be slid into place. Once in place, the bearings and shaft will be secured. The idler pulleys will then be slid onto the shaft and secured in place with shaft collars.

The verification processes are as follows:

Figure K.5.A: Contract C2, Collaborative Prototype Drive Modification

- The wheels hubs will be verified through visual inspection of the rotation of the wheel and tread alignment
- The belt tensioner will be verified through visual inspection of the rotation of the wheel and tread alignment

The deliverables for this contract include:
- Custom Wheel Hub DMIV
- Tensioner DMIV

Interfacing Plan: The collaborative prototype drive modifications will be made in accordance with the prototype frame design. The motor mount bolt holes will be placed according to the specified location of the side panel motor mount hole (COD-MPK001). The verification of the custom wheel Hubs and motor mounts is dependent upon the completion of the Prototype Frame Modifications (COD-C1).

Delivery Date: 26 February 2010

MARK P. IESK		____Optional______
Student's Signature	Manager's Signature	Instructor's Signature

Figure K.5.A: Contract C2, Collaborative Prototype Drive Modification Cont..

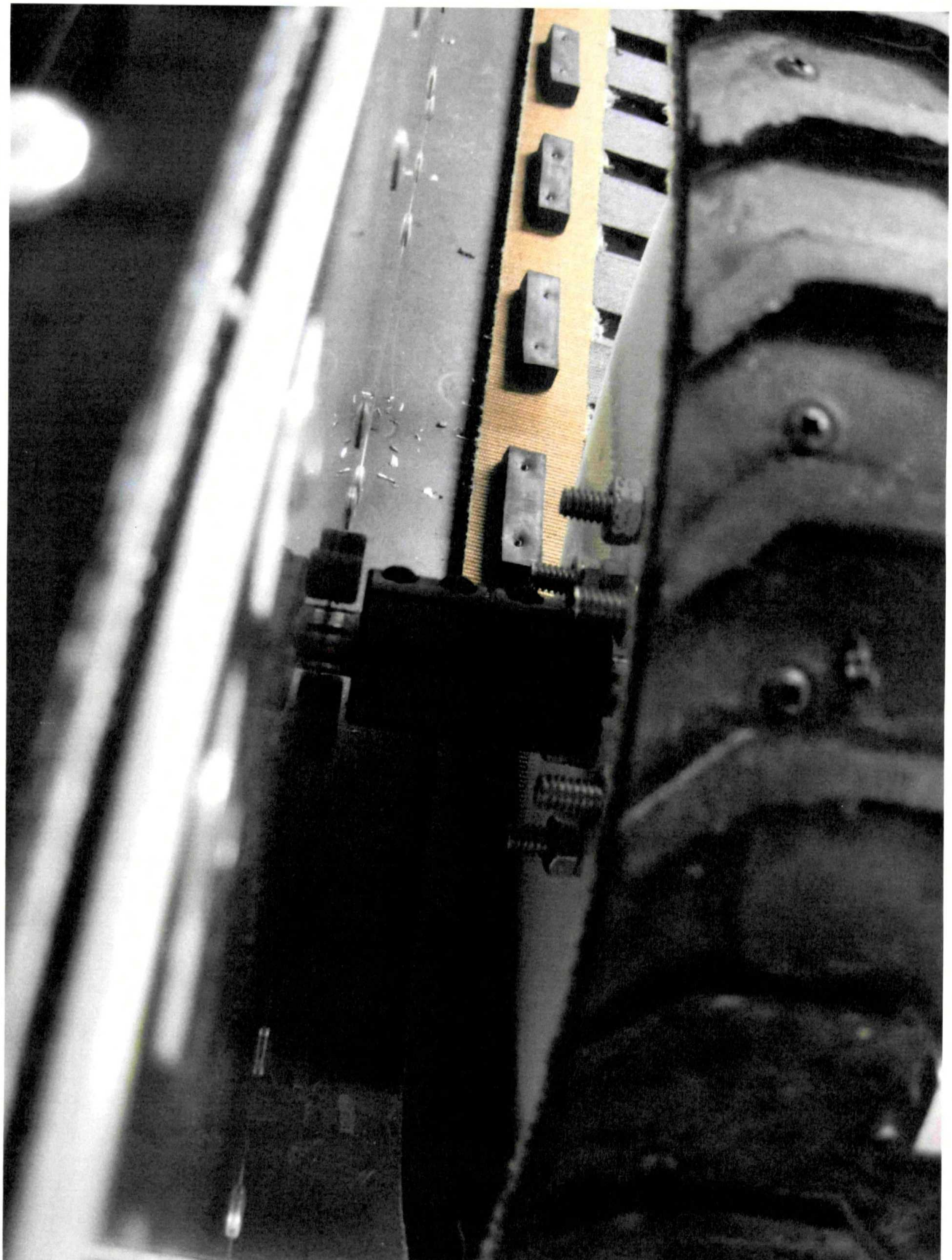


Figure K.5.A: Contract C2, Collaborative Prototype Drive Modification Deliverable